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MIDDLE TRIASSIC EVOLUTION OF THE NORTHERN PERI-TETHYS AREA AS INFLUENCED BY EARLY OPENING OF THE TETHYS OCEAN

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Abstract: During Middle Triassic times, the Germanic or northern Peri-Tethys Basin pertained to the western Tethys Ocean. The basin was closed from the north and open toward the Tethys by tectonically controlled depressions (gates). The gates were opened in different times. The marine incursions broke first (as early as in late Scythian time) through the eastern gates and from the Polish Basin advanced gradually to the west.

Semiclosed disposition of the basin resulted in its distinctive environmental diversification. Open marine environments developed along the southeastern margins which should be regarded as an integrate part of the Tethys Ocean rather than the epicontinental sea. Northward and westward from the Silesian and Carpathian domains the environments became more restricted. This resulted in significant facies diachronity between the western and eastern parts of the basin. As indicated by the faunal diversity, facies variability and geochemical properties of the sediments, during almost entire Anisian time the open marine sedimentation dominated in the eastern part while the western part displayed restricted circulation, typical for the semi-closed, evaporitic basin. The circulation reversed in Ladinian time when the westward shift of the tethyan spreading center gave rise to opening of the western gate. Meanwhile, the eastern and northern parts of the basin were uplifted and underwent emersion by the end of the Ladinian.

Evolution of the southern parts of the Germanic Basin (Silesia, Holy Cross Mts., SW Germany) has been directly influenced by the Tethys rifts. The crustal motion was transmitted from the Tethys rift onto its northern periphery by reactivated Hercynian master faults.

The Northern Germany and the North Sea basins were controlled by the North Atlantic–Arctic rift system. The central part of the basin was dominated by thermal subsidence.

Despite of the intense synsedimentary tectonism affecting the basin, the distinguished 3rd order depositional sequences resulted from eustatic controls. The concordance between the tethyan and peritethyan sequence stratigraphy argues for the overregional, eustatic nature of the sequences.

Faunal migration from the Tethys into its northern periphery followed generally the rift-controlled opening of the seaways within the Tethys. The first tethyan faunas which appeared in the south-eastern part of the Polish Basin as early as in Induan time came from the eastern branch of the Tethys Ocean (Paleo-Tethys). The next migration waves proceeded by western branches of the spreading ocean (Neo-Tethys) and entered the Germanic Basin through the Silesian-Moravian Gate (in Anisian time) and through the Western Gate from Ladinian time onward.

Abstrakt: W czasie środkowego triasu basen germański należał do północnego obrzeżenia Oceanu Tetydy nazywanego północną Perytetydą. Taka pozycja paleogeograficzna wskazuje że basen germański należy traktować raczej jako integralną część zachodniej Tetydy niż jako typowy basen epikontynentalny. Bezpośrednie połączenie między obszarem germańskim a Tetydą utrzymywane było przez system tektonicznie generowanych obniżeń (bram) rozwiniętych w obrębie speneplenizowanego lądu windelicko-bohemskiego stanowiącego strukturalną barierę między otwartym oceanem i jego strefą peryferyjną.

Przez większą część środkowego triasu basen germański wykazywał cechy basenu półzamkniętego o ograniczonej i jednokierunkowej cyrkulacji. Taki układ hydrologiczny powodował ewaporacyjny wzrost zasolenia wód basenu w miarę oddalania się od strefy dopływu wód oceanicznych. Znajduje to potwierdzenie w wyraźnym ubożeniu zespołów fauny zasiedlającej zbiornik jak i w zapisie izotopów stabilnych węgla i tlenu.

Otwieranie bram miało charakter diachroniczny i postępowało ze wschodu na zachód. Najwcześniej, bo już w środkowej części wczesnego triasu otwarta była tzw. Brama Wschodniokarpacka. W anizyku głównym połączeniem była Brama Morawsko-Śląska a w ladynie Brama Zachodnia. Diachronizm w otwieraniu bram był pochodną migracji głównej strefy spreadingu tetydzkiego, która przemieszczała się ze wschodu na zachód.

Wyróżnione dla basenu germańskiego sekwencje depozycyjne trzeciego rzędu wykazują dobrą korelację z sekwencjami z basenów alpejskich co pozwala stwierdzić, że cykle transgresywno-regresywne w basenie germańskim kontrolowane były głównie przez wahania eustatyczne.

Subtropikalna pozycja paleogeograficzna północnej Perytetydy warunkowała jej gorący i półsuchy klimat. Okresowe zwilgotnienia w późnym ladynie i w karniku były pochodną przebudowy tektonicznej i intensywnej działalności wulkanicznej w obrębie Tetydy.

Key words: Late Scythian–Carnian, Tethys, Peri-Tethys, basin analysis, sequence stratigraphy, paleogeography, paleoenvironments.

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INTRODUCTION

Middle Triassic time was decisive for the Pangea supercontinent that started then to break up and a new ocean called Neo-Tethys formed within the opened, rift-controlled seaways system (Fig. 1). The presented paper is aimed on reconstruction of the middle to late Triassic evolution of the north-eastern margin of the western Tethys Ocean, called Germanic or northern Peri-Tethys Basin. Therefore, though the study focuses essentially on the Polish and German parts of the basin, many aspects of their geological history have to be referred to the adjacent regions, including the alpine domains.

The sedimentary succession formed during late Scy-

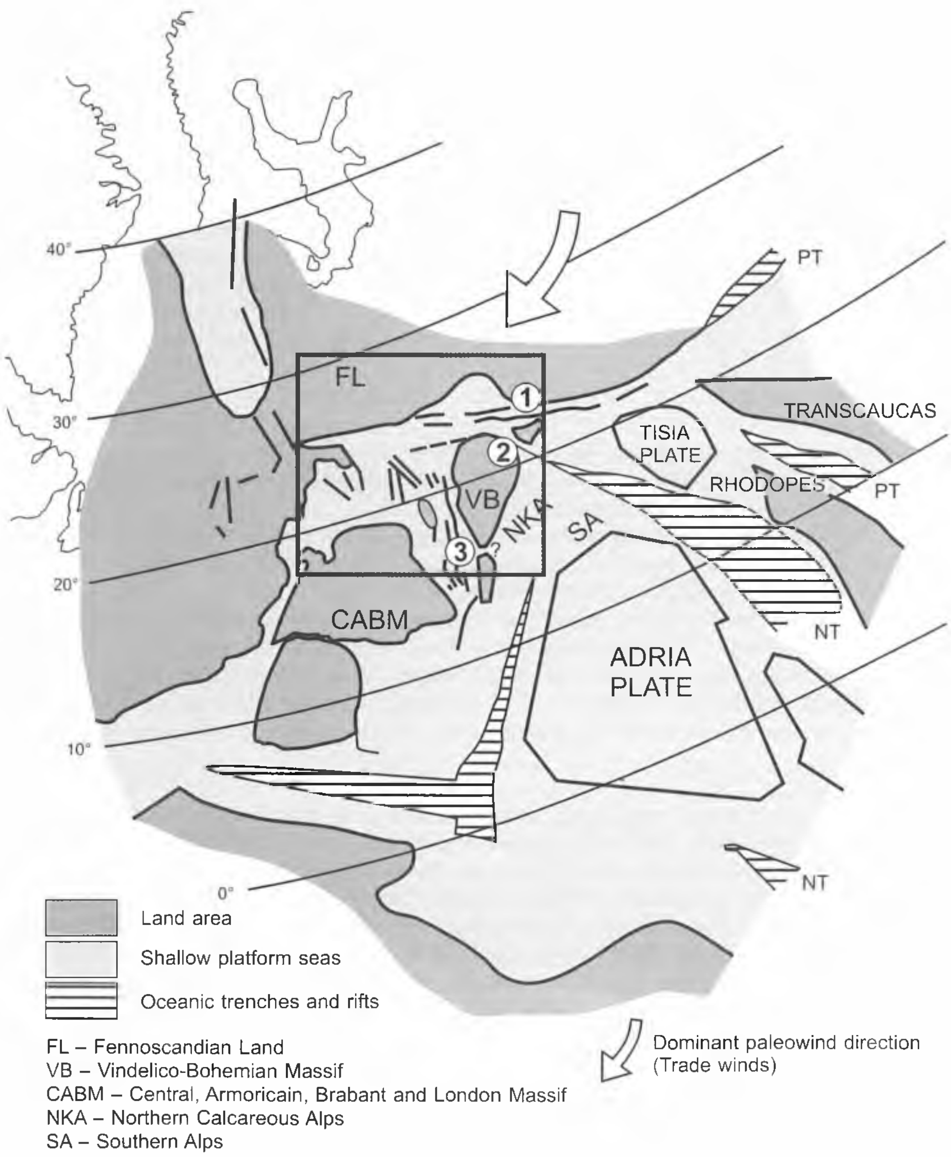


Fig. 1. Paleogeographical position of the northern Peri-Tethys Basin in Middle Triassic times. Modified from Szulc (1999). 1 – East Carpathian Gate, 2 – Silesian-Moravian Gate, 3 – Western Gate. Paleolatitudes inferred according to the Middle Triassic poles isolated by Theveniaut *et al.*, (1992)

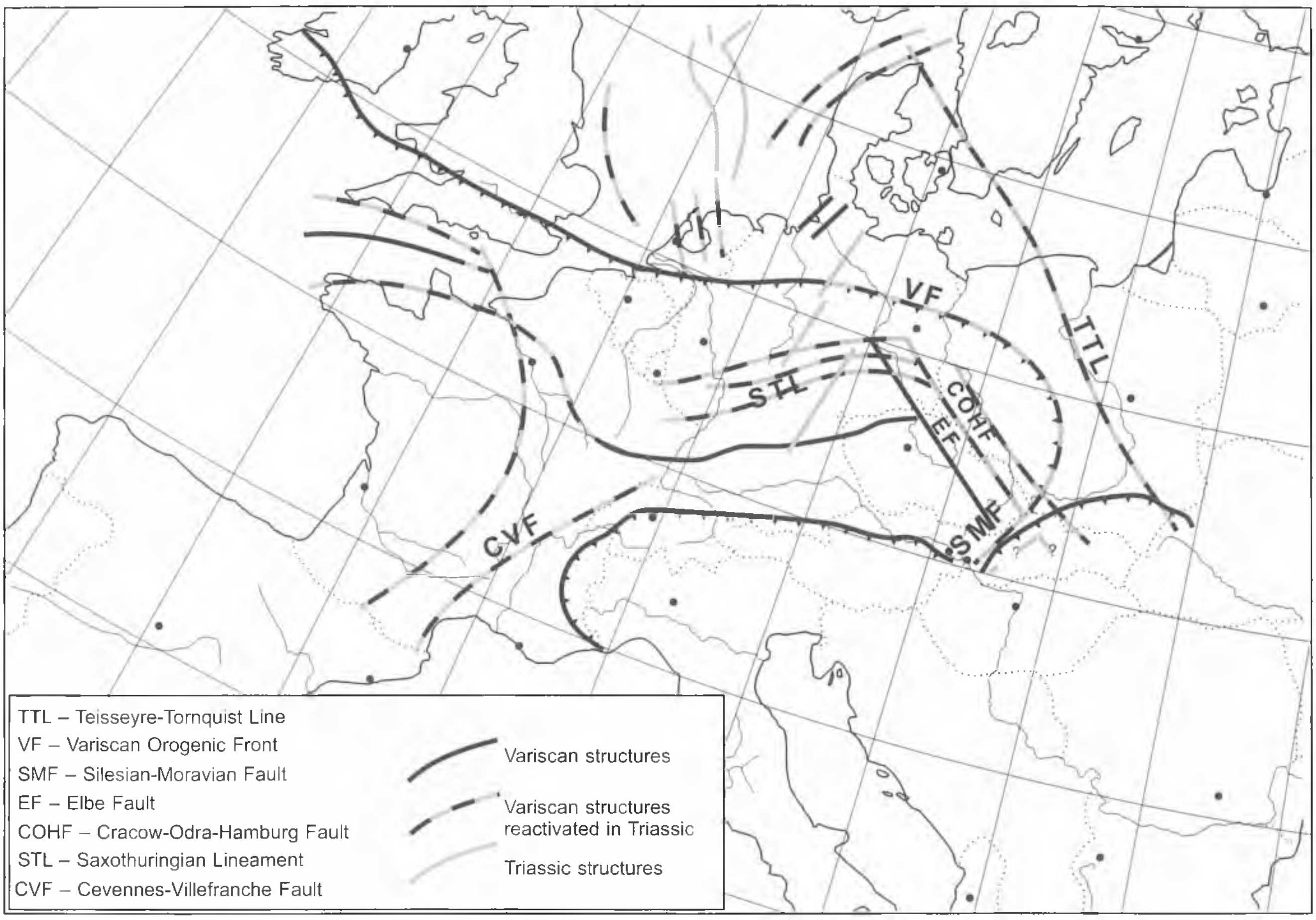


Fig. 2. Principal tectonic lineaments in Europe controlling the northern Peri-Tethys in Triassic times (after Szulc, 1999, partly modified)

thian–early Carnian time comprises lithological units distinguished as the Röt (Roetian), Muschelkalk and the lower-middle Keuper formations. In terms of sequence stratigraphy, all these units represent the principal Triassic transgressive-regressive cycle, which commenced with the Röt coastal playa deposits and terminated actually with the Schilfsandstein lowstand deposits of Carnian age.

General setting

The Triassic Germanic Basin was a tethyan periphery basin, closed to NE and E by the Fennosarmatian Land and to the west by Hercynian blocks of the Central, Armoricain, Brabant and London Massifs (Fig.1). To the south, the basin was separated from the Tethys by the Vindelico-Bohemian Massif. Tethys Ocean communicated with its northern periphery by system of seaways: the East Carpathian, Silesian-Moravian (or Silesian) and Western ("Burgundy") Gates. The gates disposition and generally the basin topography were controlled by inherited Hercynian structures (Fig. 2; Szulc, 1993). Such a situation of the Germanic area, strongly affected sedimentary processes in the basin and finally resulted in a modification of eustatic fluctuations by regional or local tectonic controls. Diachronous sedimentary successions resulted from earlier transgression and earlier ultimate regression in the eastern (Polish) basin is the most outstanding feature of the Peri-Tethys evolution during Middle Triassic times. The eastern gate was opened already in late Induan time while the western communication developed only during the Pelsonian. The diachroneity is explained as resultant from westward relocation of the connection tracts following the shift of the Tethys spreading center (Szulc, 1997a).

Posthercynian structural framework and the early Triassic of the Germanic Basin

During the earliest Triassic (lower Buntsandstein) the basin configuration followed basically the Zechstein disposition with a subsidence center situated upon the Teisseyre-Tornquist Zone. The only new Triassic structure was the Cracow–Tarnów Depression (Szyperko-Teller, 1997) separated from the northern and northwestern basin by an elevated range, encompassing Sudetes Mts. Małopolska and Lublin Massifs (Fig. 3). The both parts varied in basin evolution, particularly in Induan time (lower Buntsandstein–lower middle Buntsandstein). The deposits of the lower Buntsandstein are fine-grained clastics with a high proportion of oolitic beds typical for the entire German (Geluk & Röhling, 1997) and northern Polish early Triassic succession. As evidenced by sedimentological studies (Pieńkowski, 1989) and paleontological data (Fuglewicz, 1980) the northern and western basins were strongly influenced by marine ingressions coming from the NW (i.e. from the Bo-

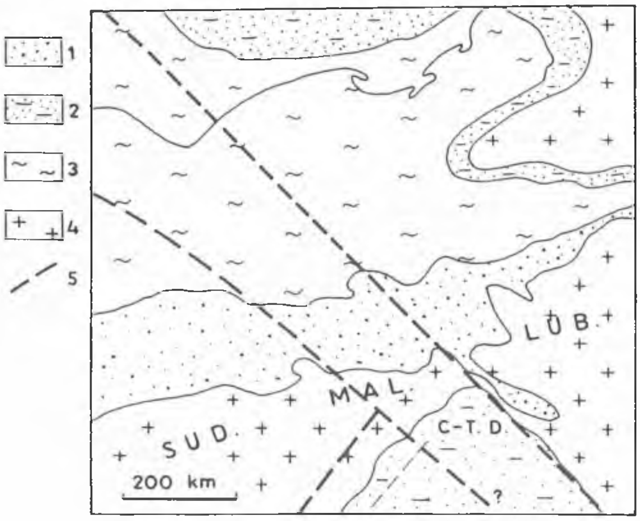


Fig. 3. Early Triassic (lower Buntsandstein) facies distribution within the eastern part of the Germanic Basin. *1* – continental coarse-grained clastics; *2* – fine-grained clastics; *3* – limnic/brackish muddy deposits (including oolitic shoals) with shallow marine incursions; *4* – land area; *5* – principal faults. Facies distribution partly after Szyperko-Teller (1997), changed and modified. Sud. Mal. Lub. – Sudetes-Małopolska-Lublin Massif; C-T. D. – Cracow–Tarnów Depression

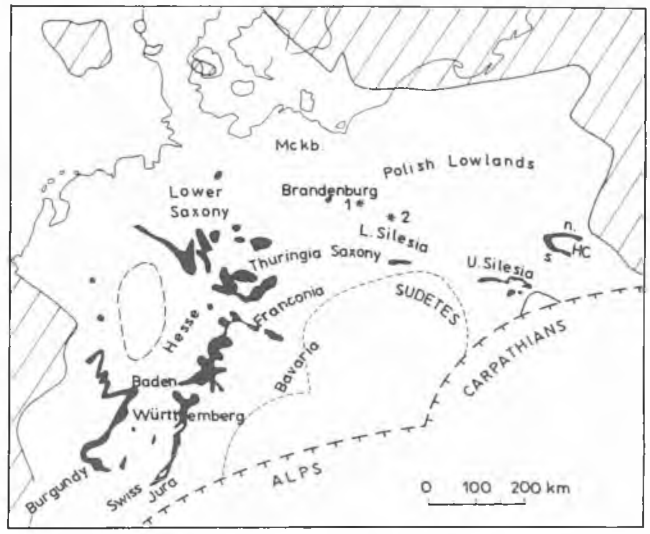


Fig. 4. Main outcrops of the Middle Triassic rocks in the area of the Germanic Basin. After Hagdorn (1991), simplified. Mckb. – Mecklenburg, HC – Holy Cross Mts. Asterisks mark position of the boreholes Ośno (1) and Otyń (2) described in the paper

real Sea) while in the Cracow–Tarnów Depression a coarse clastic, fluvial sedimentation dominated (Fig. 3; Szyperko-Teller & Moryc, 1988). It seems very likely that the Depression was controlled directly by the Tethys spreading belt since the first tethyan fauna occurs here already in the lower middle Buntsandstein deposits (late Induan) (Głowacki & Senkowiczowa; 1969; Milewska & Moryc, 1981). This proves that the Cracow–Tarnów Depression was a predecessor of the eastern gates system linking the Tethys Ocean with the Germanic Basin. Unfortunately we have no complete data about the Hercynian basement covered by the Carpathian orogen. However regarding strike and nature of the main Hercynian (or older) faults in the southeastern part of the Polish Basin (Dvořak, 1985; Cech & Zeman, 1988), one may presume that the basement was dissected by a system of oblique faults resulting in fault-bounded blocks (Figs. 2, 3).

RESEARCH GOALS AND METHODS

The main goal of the paper, i.e. the reconstruction of the basin evolution, bases on an integrated study of depositional sequences from the whole basin area. The Triassic of Silesia, the Holy Cross Mts. and SW Germany has been chosen for more detailed studies because of frontier position of these regions, situated between the Tethys and Germanic Basin.

Due to space constrains and for the sake of better comprehension of this encapsulating paper, I have decided to compile the basic data in form of graphic displays whereas the descriptive part has been limited to necessary elucidations and guides to the illustrations.

Analytical data come from the present author's investigations on the Röt–lower Keuper outcrops in Poland (Upper and Lower Silesia, Holy Cross Mts.) and Germany (Brandenburg, Thuringia, Baden-Württemberg; Fig. 4) as well as from published and archival data (mostly well-log data published in series of the "Profile głębokich otworów wiertniczych" by the Polish Geological Institute). The Germanic Triassic has been referred to relevant Triassic sections from the Tethys domain. The last-named data come both from published sources and from author's field studies carried out in the Prealps Medianes, Western Alps (Briançonnais domain), northern Dolomites, Engandiner Dolomites, Northern Calcareous Alps (Karwendel Group), eastern Carnic Alps, Eastern Calcareous Alps and the inner Carpathians (Mecsek Mts, Slovakian Karst, Fatra Mts.). Some of the published data were revised and reinterpreted in terms of paleoenvironmental analysis and sequence stratigraphy procedure. About 60 sections have been studied in details over the last 10 years. Most of them have adequate stratigraphical dating, determined by means of biostratigraphical and ecostratigraphical examinations. As result, a chronostratigraphical correlation of the examined sequences throughout the whole basins has been assessed. New results of the magnetostratigraphic study of the Röt–Muschelkalk succession from southern Poland (Nawrocki & Szulc, 2000) allow a better timing of the more pronounced events in the basin history and their correlation with the Alpine basins.

The fundamental database obtained in form of measured sections was intepreted in terms of lithofacies and depositional environments, regarding petrographic characteristics, sedimentary structures, paleoecological and paleobathymetrical indicators, diagenetic fabrics, energy levels etc. Finally, instead of the space-consuming description to the analysed sections, I have synthesised the elaborated material in form of paleofacies maps for several key intervals of the late Scythian–early Carnian time span (see Fig.12). A correlative setting of the stratigraphically-guided sections, enabled restoration of facies distribution within the Germanic Basin. It must be stressed however, that the basin borders, especially the southern margins should be treated as very conjectural because of postsedimentary erosion upon the Vindelico-Bohemian Massif. This concerns in particular the intervals of the most pronounced transgressions, reaching probably much more far to the south as we could figure after the recent occurrence of the Triassic rocks.

The isopach maps constructed separately for the lower and upper Muschelkalk have been used to visualise a shift of the subsidence center during Anisian–Ladinian time.

As the next purpose, a new sequence stratigraphical scheme for the late Scythian–Carnian interval of the Germanic Basin has been worked out. The distinguished third order depositional sequences have been defined as genetically- related strata successions, bounded by unconformities forming sequence boundaries. The defined boundaries represent Type 1 of the sequence boundary (*sensu* Haq *et al.*, 1987), e.g. subaerial exposure surfaces, facies discontinuity or erosional discontinuity. Since the study was based mostly on outcrop and borehole data, Type 2 boundaries, i.e. the "discrete", seismic stratigraphic discontinuities, were not identified. The distinguished depositional sequences have been divided into systems tracts encompassing lithofacies assemblages represented the lowstand systems tracts (i.e. lithofacies assemblage overlying sequence boundary and arranged in an agraddational stratal pattern), transgressive systems tracts, featured by backstepping stratal pattern and the highstand systems tracts characterised by agraddational/forestepping stratal pattern (Sarg, 1988). The systems tracts were defined by analysis of parasequences stacking, undiscussed in details (with some excepts) in the present paper. Sedimentological analysis of the systems tracts, enables a plausible reconstruction of the basin dynamics (e.g. transgression rate, subsidence intensity etc.) for a given depositional sequence. Finally, the maximum flooding surfaces were typified after analyses of sedimentological, paleobiological and geochemical criteria. Last but not least, the trace fossils were used as a helpful tool by defining the systems tracts and maximum flooding events. For sake of simplicity the following abbreviations are used in the text: LST for lowstand systems tracts, TST for transgressive systems tracts, and HST for highstand systems tracts.

The sequence stratigraphic framework of the Germanic Triassic by Aigner and Bachmann (1992) is based on data from Germany, i.e. only from the western part of the basin. The present study encompasses data both from the western (Germany, Denmark, France, England) and from the eastern (Poland, Lithuania, Belarus) basins. The stratigraphical guides of the proposed framework are more precise nowadays, due to a significant progress in paleontological and geophysical studies done during the last years. Because of the above mentioned facies diachroneity, the lower, i.e. the late Scythian–Anisian part of the proposed sequence stratigraphic framework has been defined in the eastern (Silesian mostly) part of the basin, where the Röt and lower Muschelkalk are represented by marine carbonates rich in fossils of biostratigraphical importance. For the same reason, the upper part of the scheme, i.e. from the middle Muschelkalk onward, is based on studies from the western (German) part of the basin. Because of the postsedimentary erosion upon the Vindelico-Bohemian Massif, the problems with unequivocal defining of some important sequence boundaries still remain, however.

The Middle Triassic paleogeography and structural evolution of the western Tethys has been compiled by many authors (e.g. Ziegler, 1988, 1990; Dercourt *et al.*, 1993) but owing to the late Cretaceous–Tertiary accretion an accurate palinspastic reconstruction for the different tectonic units of the Alpine orogen is controversial. This in turn makes also ambiguous the paleogeographical reconstructions of the alpine basins (cf. e.g. Zacher & Lupu, 1999). To omit this obstruction, I have assumed that a comparative sequence stratigraphic correlation of different basins could substantially improve the reconstructions. Such a procedure allows to decipher the facies changes controlled by global eustatic mechanism from those resulted from local tectonic controls. Furthermore, my sofar carried out investigations on direct symptoms of the Triassic synsedimentary tectonics have been synthesized and used to check the inferred surmises on tectonic controls. Finally a notable affinity of tectonic evolution between given basins has been employed in this paper as a decisive criterion indicating their close paleoposition within the tethyan and/or peritethyan domains during the studied interval.

In order to refine paleoenvironmental reconstruction for the late Scythian–early Carnian in the northern Peri-Tethys area, ^{13}C and ^{18}O analyses have been made for the carbonates (both bulk, calcilutite samples and brachiopods) from 4 profiles of the Polish basin (see Figs. 25–28). The Upper Silesian profile represents the Tethys-faced part of the Germanic basin, the section from NE margin of the Holy Cross Mts. would reflect the influences from the Eastern Carpathian Gate whereas the Lower Silesian (Raciborowice section) and the western Poland (Ośno section) were chosen to control the lateral evolution of water chemistry. In order to minimalise the possible diagenetic overprint, the samples have been subjected to standard selection procedure (Grossman *et al.*, 1991; Hoefs, 1997) with regarding the CAI index of the conodonts from the examined sections. The geochemical data applied to paleonvironmental and palaeooceanographical intepretations, improved the reconstruction of the basin evolution and allowed to recognise the climate influence on sedimentary processes

As appeared evident during my studies, the Upper Silesian subbasin pertained to the Tethys domain rather than to the epicontinental Germanic province (see also below). Therefore, this area was subjected to additional, more detailed studies on paleoecological and geochemical trends in the basin. Among others, the Sr contents in the Upper Silesian Muschelkalk has been applied as a complementary check-tool of the possible evaporation effects. Afterward these data have been compared with published results from the central and southwestern parts of the basin (Riech, 1978; Langbein & Stepansky, 1996).

LITHOSTRATIGRAPHY, BIOSTRATIGRAPHY AND MAGNETOSTRATIGRAPHY OF THE GERMANIC BASIN

I have decided to use the traditional and broadly known names of the lithostratigraphical units, though some of them are informal in terms of the stratigraphical nomenclature. For sake of clarity I present below the other, occasionally used equivalents of the chosen unit names.

The Middle Triassic of Silesia has a very consistent division established by Assmann (1933, 1944) and this system has been generally accepted. Assmann (1933, 1944) has divided the Upper Silesian Middle Triassic into the "Schichten" (beds) which in fact fulfil the recent lithostratigraphical definition of the formations. Since the lithostratigraphical nomenclature is of subordinate significance for the main purpose of the present paper I have translated the Assmann's "Schichten" as "Beds" and use this term in sense of formation. However, considering new biostratigraphical data and sedimentological criteria (including the sequence stratigraphical context) I made some necessary changes in the Assmann's scheme (see Fig. 25). The most important change is the shift of the evaporitic/restricted Tarnowice Beds from the upper Muschelkalk to the middle Muschelkalk group. Furthermore, the successive sediment package of the lower upper Muschelkalk displays an obvious entirety in lithological and sedimentological features, hence instead of two units introduced by Assmann (Georgendorfer Schichten and Wilkowitzer Schichten) I treat them as one unit (Wilkowice Beds). Some other changes (mostly nominative) have been proposed by Kotlicki (1974) which renamed the uppermost Röt ("Myophoria Beds") as Błotnica Beds, the Terebratula Beds as Dziewkowice Beds, the Diplopora (Dolomite) Beds as Jemielnica Beds, the Wilkowice Beds as Rybna Beds, the lower Keuper as Miedary Beds, the Grenzdolomit as Opole Beds and the Schilfsandstein as Piotrowina Beds. Bilan (1976) used the names Chrzanów Formation and Bolesław Formation to the lower and Schilfsandstein respectively of the Silesian-Cracow region.

The generally accepted lithostratigraphical division of the Triassic succession of the Holy Cross Mts. has been erected by Senkowiczowa (1970) and this scheme is applied also in my work however, under the same conditions as for the Assmann's nomenclature. Unfortunately, in contrast to the Silesia, the nowadays outcrops of the Middle Triassic rocks in the Holy are rare and their quality is not sufficient for detailed sedimentological studies and for unequivocal defining of the depositional sequences (see Fig.9).

The central and western parts of the Polish Basin show similar facies development as the Brandenburgian and Thuringian subbasins, hence their lithostratigraphical subdisivion has been directly adapted in the Polish literature (Gajewska, 1971). The only noteworthy exception are the Barwice Formation as the Röt equivalent (Szyperko-Teller, 1982) and the Sulechów Beds corresponding to the lower Keuper of Germany (Gajewska, 1978).

I have applied traditional litostratigraphical names also for the Triassic succession in Germany although a new lithostratigraphical scheme has been introduced in last years by the German Stratigraphic Commission (see e.g. Bachmann, 1998). I believe that some of the traditional units named after dominating lithology or typical fossils, e.g. Wellenkalk or Ceratites Beds are more useful for sequence stratigraphical aims than their formal counterparts, i.e. the Jena Formation or Meissner Formation, that before the use need first a detailed descriptive definition. Beside the above units, the other traditional units mentioned in this text have been replaced as follows: the Gesilinger Bank, orbicularis Beds (middle Muschelkalk) by Karlstadt Formation, the Lettenkeuper (or lower Keuper) by Erfurt Formation, the lower Gipskeuper by Grabfeld Formation and the Schilfsandstein by Stuttgart Formation

The already noted facies diachroneity within the northern peritethyan area caused many difficulties for an unequivocal basinwide correlation of the Triassic lithostratigraphical units despite of their formal or informal character. The only tools for correlation of the units are reliable biostratigraphical marker horizons and/or magnetostratigraphical zonation. First modern attempt of biostratigraphical correlation of the lithostratigraphical units carried out by Kozur (1974), was based on integrated biostratigraphical studies of cephalopods, ostracods, pelecypods, holothurians and especially the conodonts. Conodont stratigraphy enabled a relatively precise correlation of the Muschelkalk sequence with the Alpine Middle Triassic. The Muschelkalk biostratigraphy has been improved by investigations of crinoids and echinoids done by Hagdorn and Głuchowski (1993).

Unfortunately, because of an underestimation of paleobotanical tools for biostratigraphical dating a reasonable correlation between the marine and continental facies within the Germanic Triassic still remains doubtful. There were hitherto only few attempts applying paleobotanical data to the overregional facies correlation (see e.g. discussion by Orłowska-Zwolińska, 1984, 1985; Visscher *et al.*, 1993; Wierer, 1997). It seems that beside the magnetostratigraphy, an application of the sequence stratigraphy based on integrated biostratigraphical data, palynological including, is the only way to approach the problem of regional lithofacies variation and correlation. In the present paper the paleobotanical (mostly palynological) and paleozoological documentation has been applied for biostratigraphical correlation of the defined depositional sequences.

Summarizing, the biostratigraphical guidelines of the proposed sequence stratigraphic framework are based on conodont biozonal subdivision (Kozur, 1974; Zawidzka, 1975; Trammer, 1975; Götz, 1995; Kędzierski, 1996; Narkiewicz, 1999), crinoids (Hagdorn & Głuchowski, 1993) and palynological biozonation well established in the Polish part of the basin (Orłowska-Zwolińska, 1977, 1983, 1985; Gajewska, 1978). The biostratigraphical subdivision of the alpine sequences has been constructed on the ammonites biozones (Brack & Rieber, 1994) and condodonts (Krystyn, 1983) (see also discussion by Rüffer & Zühlke, 1995). These both index fossils have been also applied for preliminary correlation of the alpine successions with the Muschelkalk deposits (Kozur, 1974; Brack *et al.*, 1999).

The mentioned new magnetostratigraphic data (Nawrocki, 1997; Nawrocki & Szulc, 2000) tied to the conodont biostratigraphy, appeared helpful for detailed correlation of the Röt–Muschelkalk succession with the reference successions constructed for the Tethys realm (Muttoni *et al.*, 1998). Moreover, the obtained magnetostratigraphic scale allowed to precise the late Scythian–Ladinian chronostratigraphy of the Germanic Triassic within the intervals which are devoid of age-diagnostic macro- and microfossils.

SEQUENCE STRATIGRAPHIC FRAMEWORK AND EVOLUTION OF THE GERMANIC BASIN IN LATE SCYTHIAN–EARLY CARNIAN TIME

RÖT[1]

According to the magnetostratigraphic scale obtained recently for the Röt–Muschelkalk succession in Upper Silesia and the Holy Cross Mts. (Nawrocki & Szulc, 2000), the Scythian/Anisian boundary of the Polish Triassic lies within the lowermost Gogolin Beds (and within the Wolica Beds in the Holy Cross Mts.). This denied the hitherto assumed Anisian age for the entire Röt succession (Kozur, 1999). Nevertheless the new position of the Anisian lower boundary, is of subordinate importance for the sequence stratigraphical procedure and does not change significantly the earlier defined sequence stratigraphic framework of the Germanic Basin (Szulc, 1999).

1st late Scythian Sequence (S 1)

The sequence boundary is determined by a basinwide unconformity separating the middle Buntsandstein deposits from the younger successions (see Fig. 8). In Upper Silesia the sequence begins with clastic mudflat deposits (LST) succeeded by dolomites and oolitic limestones (HST) (Fig. 5) abounding in gastropod and pelecypod coquinas (Assmann, 1933). The maximum flooding surface of the sequence is defined by horizon(s) with cephalopods (*Beneckeia tenuis*) occurring in the upper part of the succession (Fig. 5).

Open marine conditions dominated also within the East Carpathian Gate domain where intraformational conglomerates, ubiquitous *Rhizocorallium commune* ichnofossils and crinoid debris make this sequence similar to the typical Muschelkalk deposits (Moryc, 1971).

To the W and NW from Silesia and the Holy Cross Mts. the carbonates were replaced by gypsum and halite (Fig. 6). Occurrence of the latter evaporite delineates the basin depocenter which stretched from western Poland to eastern England (see Fig. 12A). The late highstand deposits are represented by fine-grained mudflat facies. At the western and northwestern basin margins the evaporites pass into clastic mudflat and sandflat deposits (Warrington, 1970; Bertelsen, 1980).

The outlined facies distribution along with the isopach pattern (Fig. 7) indicate that the Germanic area formed a semi-closed, evaporitic basin fed by the tethyan waters *via* the Silesian-Moravian Gate and locked from the other sides (Szulc, 1999).

Fossils and paleoeocological records

Fauna distribution (mostly gastropods and pelecypods) clearly matches the sedimentary facies pattern. The richest faunal assemblages (see Fig. 18) occurred in the open marine carbonates of the Silesian and East Carpathian Gates area while basinward, i.e. within the evaporitic facies, the assemblage became impoverished. This concerns in particular the ecostratigraphic fossils (*sensu* Hagdorn & Simon, 1993): *Costatoria costata* and *Beneckeia tenuis* which enabled the recognition of the Röt facies diachroneity over the entire Germanic Basin (Szulc, 1999). These fossils have been also used for deciphering the marine ingression pathway which proceeded through the Silesian Gate and progressed to Lower Silesia and farther westward along the Saxothuringian subsidence center.

The transgression which came over the East Carpathian Gate did not exceed the Holy Cross Mts. area owing to bathymetric and chemical barrier located NW from the Holy Cross Mts (Szulc, 1999).

As proved by the paleobotanical studies (Orłowska-Zwolińska, 1977; Fuglewicz, 1980), the megaspores and miospores may be successfully applied in identification of the transgressive-regressive cycles developed within clastic deposits of the Röt sequences. For instance, the *Triletes validus* megaspores appeared always during the transgressive phases whereas the sequence boundaries and the LST sediments are impoverished or devoid of megaspore and miospore remnants.

Basin evolution

A very low subsidence rate (as reflected by the isopach pattern, Fig. 7) and open marine environment dominating in the Upper Silesian area, indicate that the Silesian Gate was a stable threshold belt, directly influenced by the tethyan waters. The threshold was dissected by deep grabens providing communication between the Tethys and the Germanic Basin (Szulc, 1999). The East Carpathian Gate was a depression homoclinally inclined to the south, i.e. toward the Tethys belt.

This all suggests that the Silesian and East Carpathian Gates were directly influenced by tectonic motion evolved within the tethyan rift. The inner part of the Germanic Basin was controlled by thermal subsidence with subsidence centers superimposed upon the Odra–Hamburg Fault and the Saxothuringian lineament (cf. Fig. 2 and Fig. 12A).

The south-western part of the Germanic Basin, including the future Western Gate, was dominated by continental sedimentation (Ricou, 1963; Courel (coord.), 1984).

2nd late Scythian sequence (S 2)

A subaerially weathered horizon making debris pavement upon the oolitic limestones defines the boundary of the sequence in the Upper Silesian region (Fig. 5). The bound-

1 More detailed description of the discussed depositional sequences is published elsewhere (Szulc, 1999).

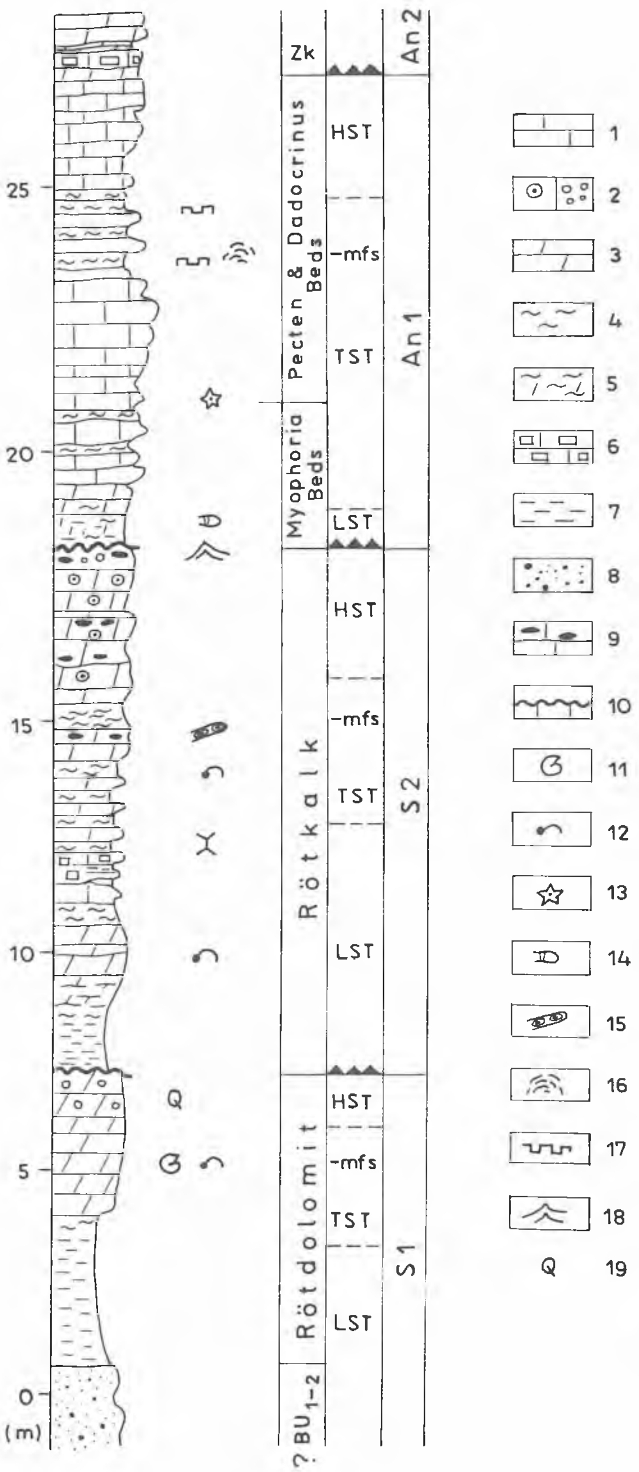


Fig. 5. Lithostratigraphic log and depostional sequences of the late Scythian and early Anisian in the Upper Silesian region (based on the profiles from the Chrzanów region). *1* – bioclastic limestones (calcarenites/calcisiltites); *2* – oncoliths and oolites; *3* – dolomites; *4* – marls; *5* – dolomitic marls; *6* – postevaporitic cellular limestones ("Zellenkalk" – Zk); *7* – claystones; *8* – sandstones; *9* – cherts; *10* – emersion surface; *11* – *Beneckeia tenuis*; *12* – *Costatoria costata*; *13* – crinoids; *14* – *Glottidia tennuisima*; *15* – dacycladales debris; *16* – *Placunopsis ostracina* bioherms; *17* – hardground; *18* – tepee fabrics; *19* – quartz sandy intercalations within carbonates

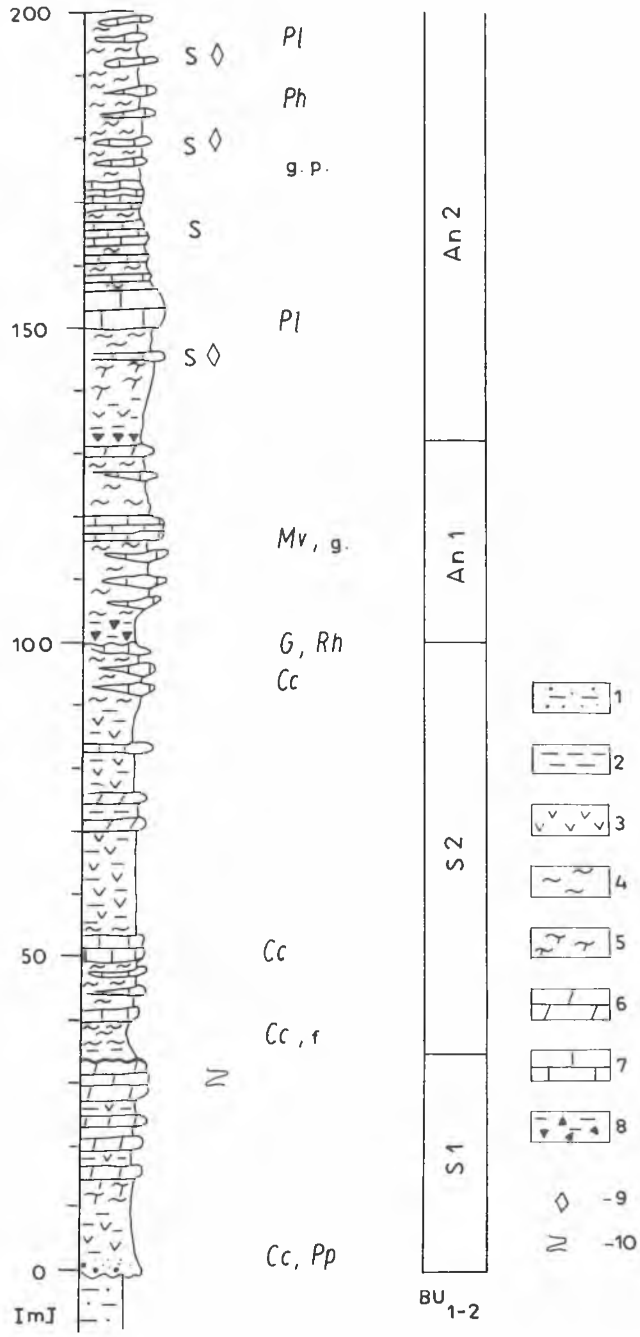


Fig. 6. Lithostratigraphic log and depositonal sequences of the late Scythian and early Anisian in the basin center (Otyń profile, western Poland). *1* – sandstones; *2* – mudstones; *3* – sulphates; *4* – marls; *5* – dolomitic marls; *6* – dolomites; *7* – bioclastic limestones; *8* – playa deposits and paleosols; *9* – celestite concentrations, *10* – slump; Cc – *Costatoria costata*; Mv – *Myophoria vulgaris*; Pp – *Paleophycus*; Pl – *Planolites*; Rh – *Rhizocorallium*; f – fish remnants; g – gastropods debris; p – pelecypods debris; s – sigmoidal deformations

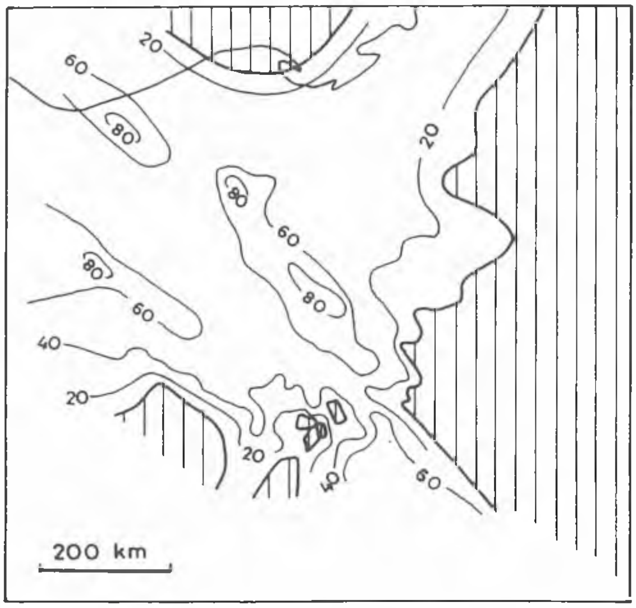


Fig. 7. Isopach map for the S 1 sequence in the eastern part of the Germanic Basin

ary is well determined at the marginal belt of the basin by erosional and paleosol horizons (Fig. 8). The clastics to the west and the evaporites to the east representing the mudflat to sabkha settings, build the lowstand systems tracts.

The transgressive and highstand system tracts in the Upper Silesia and East Carpathian Gate areas are composed by calcareous sediments (Figs. 8, 9). They grade basinward to dolomites and sulphates (Fig. 6). Farther to W and SW the playa/mudflat deposits ("Salinarröt") dominated. Upward-shallowing short cycles featured by paleosol horizons (Richter-Bernburg, 1974) and alternated shallow marine-continental ichnofabric succession (Knaust *et al.*, 1999) build the stacked parasequences, very characteristic for the entire area of SW Germany.

Extent of the second transgression and lithofacies distribution (except the halite deposition) were similar like during the first one.

Fauna assemblages of the 2nd sequence did not differ significantly from the first sequence but the absence of cephalopods.

LOWER MUSCHELKALK

1st Anisian Sequence (An 1)

Meteorically altered halite-bearing carbonates called "cavernous limestones" (Zellenkalk 1) form the sequence boundary in Upper Silesia (Fig. 5). The cavernous limestones represent a restricted inner ramp (lagoonal) environment featured by frequent emersion events (Bodzioch & Kwiatkowski, 1992). At the basin margins the boundary is defined as incised valley system filled with lowstand fluvial clastics of the Volzia Sandstone, Rötquarzit and Upper Plattensandstein (Fig. 8). In the basin center the fluvial deposits are replaced by playa redbeds with soils (Fig. 6).

The TST is represented by bioclastic limestones occurring from Silesia to Thuringia and called informally the "Myophoria Beds". To W and SW the calcareous deposits are replaced by shallow water dolomitic and siliciclastic deposits (Fig. 8). In Upper Silesia the TST is well expressed by tempestite set that displays a fining and thinning upward trend, reflecting retrograding geometry (see Fig. 11A). A hardground horizon encrusted by *Placunopsis* oyster bioherms (reaching 20 cm in height) (see Fig. 23E) occurring in this part of the section can be pointed out as the maximum flooding surface. The above lying part of the set shows a reverse shallowing/thickenning upward tendency typical of the HST. The subsequent marls, dolomites and cavernous, postevaporitic limestones (Zellenkalk 2; Fig. 10) build the uppermost part the HST.

To the west the HST deposits are playa sediments, comprising paleosol horizons (Fig. 6; Simon, 1998). The late highstand deposits are represented by dolomites (Mosbach Beds, Liegende Dolomite, Grenzgelbkalk) correlated with the upper cavernous limestones (Zellenkalk 2) in Silesia (Hagdorn, 1991).

Fossils and paleoecological records

During the 1st Anisian transgression *Costatoria costata* declined and was replaced by *Myophoria vulgaris* which became the most common pelecypod of the entire basin. The subsequent appearance of *Dadocrinus* crinoids in the Upper Silesian subbasin evidences a free communication between Silesia and the Tethys Ocean on the one hand and allow to correlate the discussed sequence with the Tethys realm on the other hand (Hagdorn & Głuchowski, 1993). The distribution of *Dadocrinus* indicates that the normal marine conditions did not exceed the western Poland area (Hagdorn & Głuchowski, 1993).

2nd Anisian Sequence (An 2)

In Silesia the sequence boundary is defined by the upper cavernous limestones (Zellenkalk 2). As already mentioned in the western part of the basin its equivalent are dolomites displaying features of subaerial exposure (Liegende Dolomite) (Szulc, 1999). The advanced peneplanisation of the basin margins (Gaupp *et al.*, 1998) hinders sometimes unequivocal deciphering of the sequence boundary. For instance, no such boundary has been recognized sofar in the Holy Cross Mts. representing the East Carpathian Gate tract (Fig. 9).

Gradual fining of grain size and faunal evolution suggest a relatively continuous course of the transgression (Szulc, 1999). The fining-upward trend in limestones from Silesia to Hesse (Upper Gogolin Beds/Wellenkalk) shows a retrogradational stratal pattern indicative for the TST.

In the SW part of the basin the lower Wellenkalk facies are replaced by black dolomitic marls, called *buchi*-Mergel (Fig. 8). The marls formed in closed southwestern end of the Germanic Basin. Restricted circulation resulted in dysoxic-euxinic conditions and favoured the accumulation of organic rich, black muds. Episodic appearances of marine organisms (*Beneckeia tenuis*, *Glottidia tenuissima*) record short incursions of normal marine waters coming from the east. Mixed, freshwater-marine dolomitisation process has been identified in the onshore facies of the marginal part of

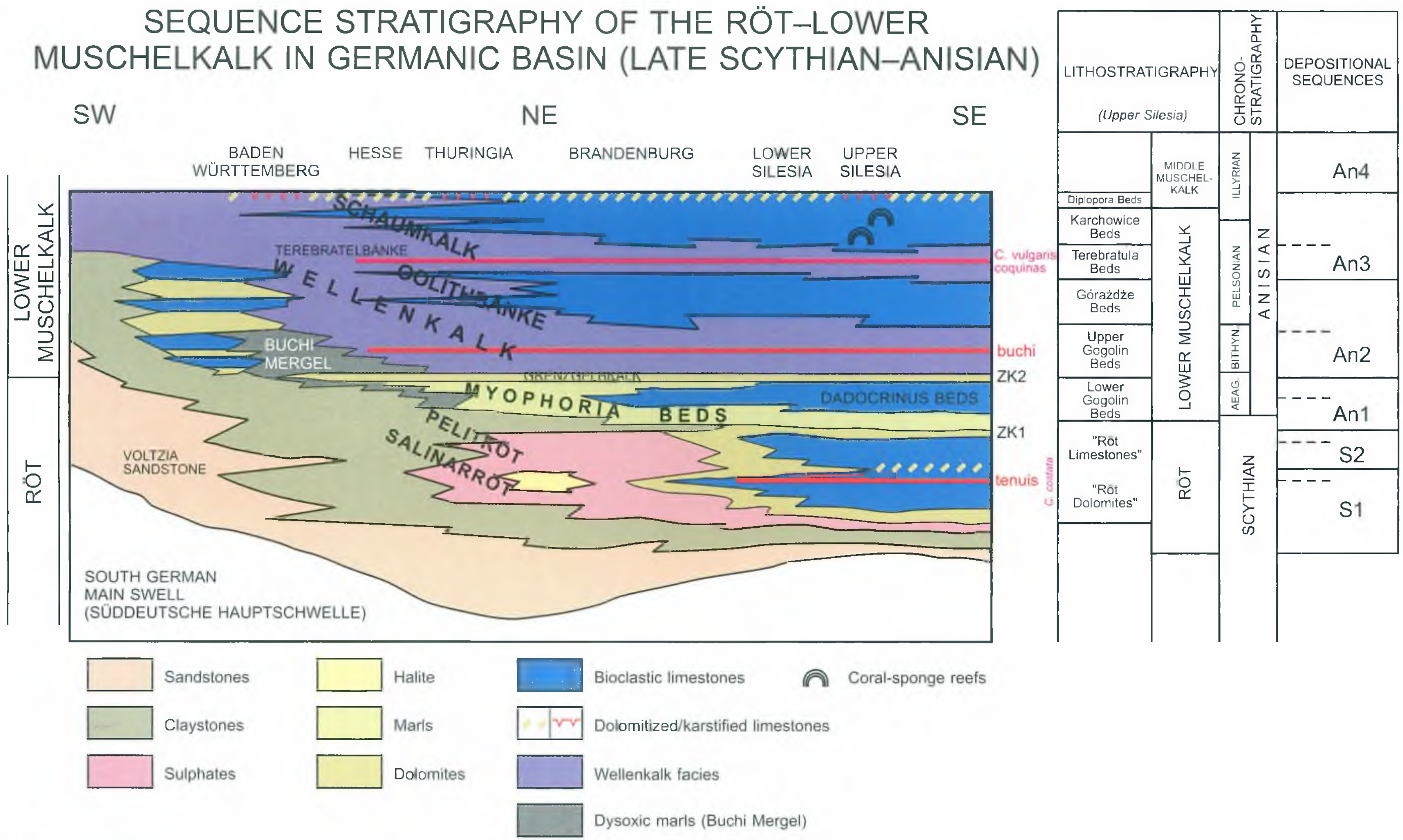


Fig. 8. Sequence stratigraphic framework of the late Scythian–Anisian from Baden-Württemberg to Silesia

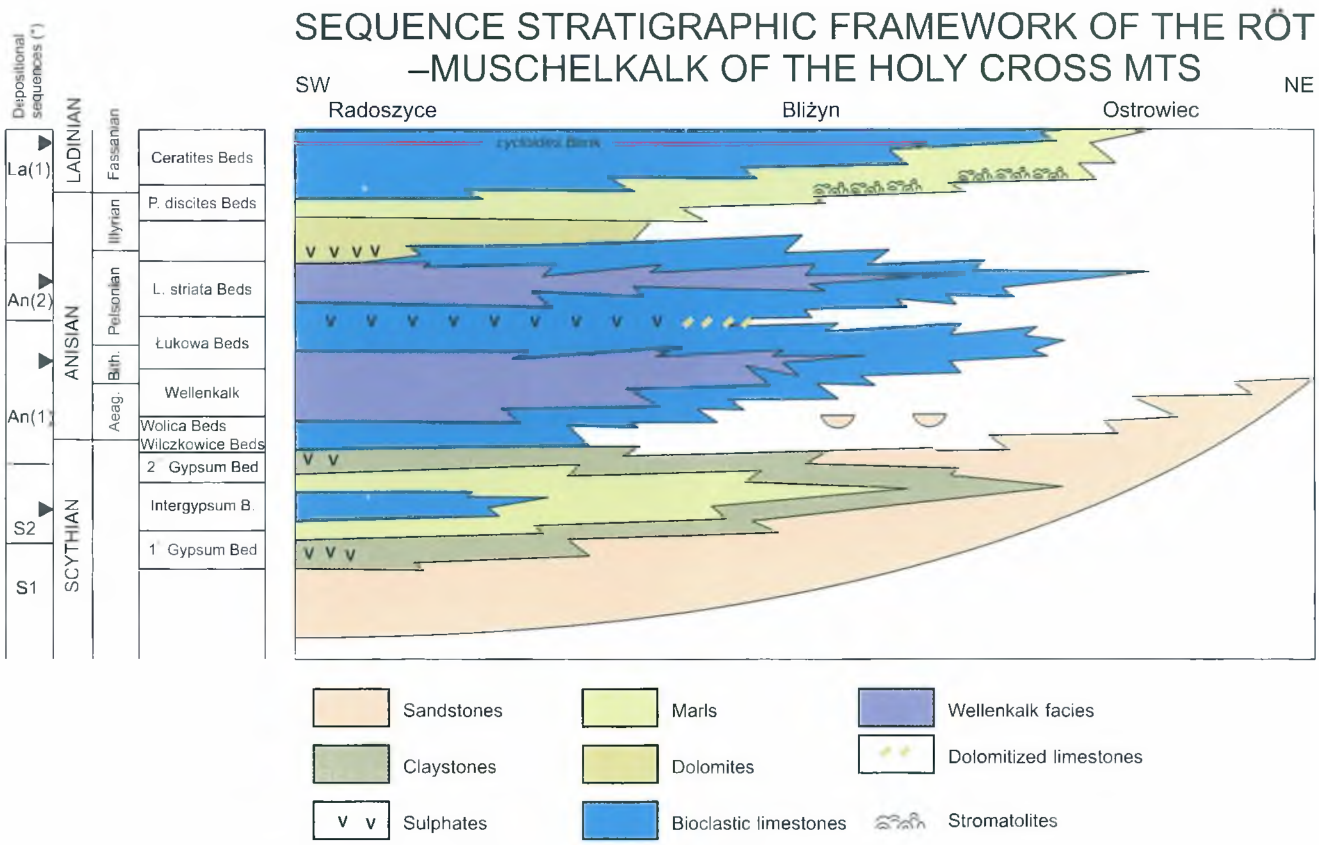


Fig. 9. Preliminary sequence stratigraphic framework of the late Scythian–Ladinian from the Holy Cross Mts. (*) Note that the numbers of the Anisian and Ladinian sequences of the Holy Cross Mts. are not equivalent of the sequences on Figure 8. The maximum flooding surfaces of the sequences An (1), An (2) and La (1) respond respectively to the maximum flooding surfaces of the sequences An 2, An 3 and La 1 from Fig. 8

the SW German basin (Szulc, 1999).

During the highstand phase the basin was progradationally filled with skeletal debris, oncoids and ooids building a thick calcarenitic bar (Figs. 11B, 11C). In the eastern and central parts of the basin its thickness ranges between 15 m in Upper Silesia (Górażdże Beds) to 10 m in the central part (western Poland, Brandenburg). In the Holy Cross Mts. the highstand deposits are represented by massive limestones of the Łukowa Beds featured by *Balanoglossites* firmgrounds (Kaźmierczak & Pszczółkowski, 1969). To the west and southwest the sandbody grades into 2–3 horizons of the so called Oolitic Beds (Oolithbänke) reaching 2–4 m of total thickness in Hesse and Baden (Fig. 8). The topmost part of the calcarenitic shoals displays common features of subaerial exposure (Szulc, 1999) and define the boundary of the next depositional sequence.

Fossils and paleoecological records

First appearance of the index conodonts is the most important bioevent recorded in the 2nd Anisian sequence. They have enabled a reliable correlation of the Muschelkalk deposits with the tethyan successions (Kozur, 1974; Zawidzka, 1975; Trammer, 1975). Also the crinoids have been successfully applied as a precise tool of biogeographical reconstructions and chronostratigraphical zonation of the lower Muschelkalk (Hagdorn, 1985; Hagdorn & Głuchowski, 1993; Hagdorn *et al.*, 1998). *Beneckeia buchi* is very a useful fossil for lithofacies correlation of the early phase of the transgression. Beside the body fossils also the ichnofossil *Pholeus* Fiege (see Fig. 22) appeared ecostratigraphic fossil since it occurs always at the beginning the TST of the 2nd sequence (Fig. 6; Szulc, 1990, 1991).

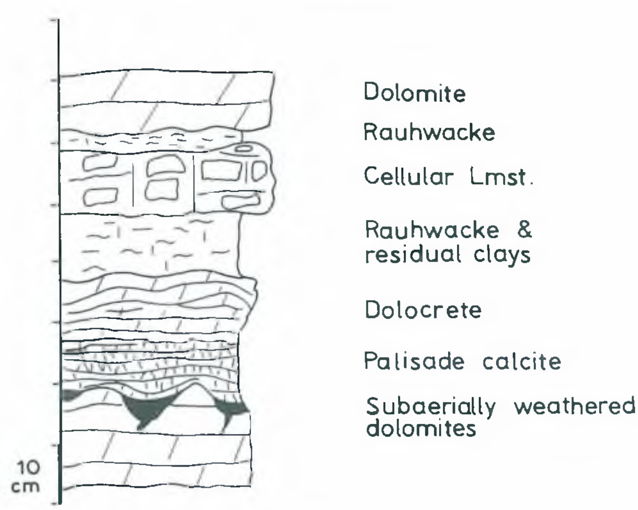
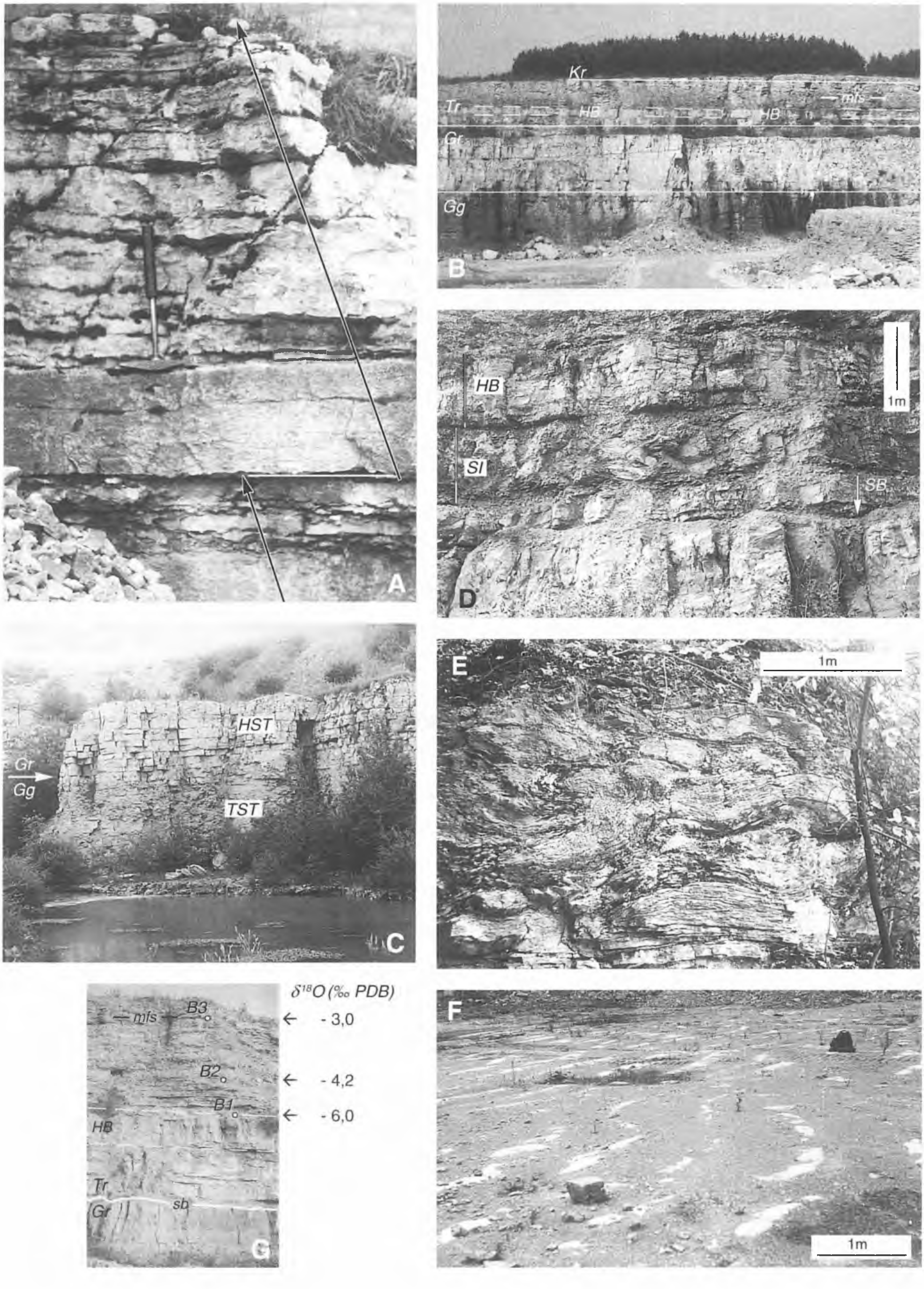


Fig. 10. Cellular limestone ("Zellenkalk 2") forming the An 2 sequence boundary in Upper Silesia. Wojkowice Quarry. The palisade calcite (*sensu* Swennen *et al.*, 1981) and the rauhwacke deposits represent the postevaporitic fabrics


A
Kr
Tr
HB
mfs
HB
Gr
Gg
B
HB
Sl
SB
1m
D
HST
Gr
Gg
TST
C
E
1m
δ18O (‰ PDB)
mfs
B3
- 3,0
B2
- 4,2
B1
- 6,0
HB
Tr
Gr
sb
G
F
1m

3rd *Anisian Sequence (An 3)*

Emersion event(s) marked by meteoric diagenetic overprints affecting the shoal deposits (Szulc, 1998) or by direct paleontological evidences (Diedrich, 1998) determine the sequence boundary within the offshore part of the Germanic Basin (Silesia, Thuringia, Hesse). In the Holy Cross Mts. the sequence boundary is marked by quartzose mudstones rich in gypsum nodules common in the upper Łukowa/lower *Lima striata* Beds (Fig. 9; Kostecka, 1978).

The transgression which followed was very rapid as suggested by the occurrence of finely laminated, deeper-water limestones which in Upper Silesia overlie directly the sequence boundary (Fig. 11D). In the Upper Silesian subbasin the deepening was tectonically reinforced (Fig. 11E, Szulc, 1991, 1993). The fine-grained limestones of the TST are impoverished in body fossils and ichnofossils what indicates a poorly ventilated, starved basin and support the above inference about a very fast progress of the transgression (Szulc, 1999). This interval is characterised by the explosive appearance of *Coenothyris vulgaris* brachiopods building the so-called Terebratula Beds (Terebratelbänke) (Fig. 8). According to sedimentological criteria (Szulc, 1990, 1993; Lukas, 1993) and palynofacies data (Götz, 1996) the transgressive Terebratula Beds represent the Anisian maximum flooding surface recognised over the whole basin (Figs. 8, 9, 12B; Aigner & Bachmann, 1992; Szulc, 1995).

After the drowning the basin was progradationally filled and the oxic condition improved gradually as indicated by infauna activity expressed by *Thalassinoides/Balanoglossites* ichnofabrics (see Figs. 22, 23) and by evolution of the benthic communities (Kaim, 1997). During the advanced highstand phase, high energy deposits (calcarenitic subaqual dunes) developed (Schaumkalk, lower Karchowice Beds) (Figs. 8, 11C, Fig. 21A). In Upper Silesia the HST climaxed with sponge-coral-echinoderm buildups (Fig. 13). Final stages of the HST in Silesia are represented by *Girvanella* oncoliths, dasycladacean debrites and eventually by oolitic bars of the Diplopora Beds.

The sponge-bearing bioclastic limestones extended up to the Holy Cross Mts. but the topmost part of the HST deposits comprises sulphate intercalations indicating elevated salinity by the end of the highstand (Kostecka, 1978).

In the central part of the basin (western Poland, Brandenburg) the reefal complex has been replaced by bioclastic and oolitic deposits of the sand shoal (Schaumkalk) reaching some 30–40 meters in total thickness. Like in the precedent sequence, the sandbody splits to SW and W, into 2–3 horizons of bioclastic and oolitic horizons sandwiched between the Wellenkalk facies. The HST terminates with dolomitic horizons enclosing sulphate pseudomorphs and displaying a relatively uniform distribution over the whole basin (orbicularis Beds, Geislingen Bank, Sub-dolomitic Beds).

Fossils and paleoecological records

Exceptionally great number of the tethyan faunal elements: brachiopods, pelecypods, echinoderms, conodonts and dasycladales occurring in the Germanic area (see Fig; 18, Assmann, 1944; Hagdorn, 1991) unequivocally indicates that during the time under discussion, the communication between the Muschelkalk Sea and Tethys Ocean reached its optimum. A development of the coral-sponge reefs confirms the open marine conditions in the Upper Upper Silesian subbasin (Fig. 13; see also the section on reefs).

It is worth noting that the very rapid transgression resulted in uniformity of environmental conditions over vast area of the basin, from the Silesian Gate to the inner parts of the basin. The environmental convergence developed from opposite starting points. As indicated by faunal and ichnofabric criteria (see the chapter on biota reactions), the rapid transgression and deepening in the Upper Silesian subbasin deteriorated oxic conditions (Szulc, 1990) and led to elevated salinity of the stagnant bottom waters. The latter phenomenon is evidenced by the increase of Sr concentration (see Fig. 25) and by celestite crystals filling primary pores (i.e. shell molds) within host carbonates. Such changes indicate substantial environmental regress with respect to, oxic and fossiliferous highstand deposits of the preceding sequence (Góraždže Beds). In contrast to the Upper Silesian subbasin, the transgression ameliorated environmental conditions in the inner parts of the basin, in respect to the precedent restricted, highly saline and fossil-poor Wellenkalk facies (Hagdorn *et al.*, 1987; Backhaus & Schulte, 1993).

Fig. 11. Chosen sedimentary characteristics of the lower Muschelkalk from Upper Silesia. **A.** Tempestite set displaying fining and thinning upward trend, reflecting retrograding TST geometry of the parasequences within the lower part of the An 1 sequence. Lower Gogolin Beds, Gogolin, Upper Silesia. **B.** General view of the Pelsonian deposits from Upper Silesia. Strzelce Opolskie Quarry. The outcrop is ca. 35 m high. *Gg* – Upper Gogolin Beds (TST of the An 2 sequence); *Gr* – Góraždže Beds (HST of the An 2 sequence); *Tr* – (Terebratula Beds – TST of the An 3 sequence) *Kr* – Karchowice Beds (HST of the An 3 sequence); *HB* – Haupterinodenbank; *mfs* – maximum flooding surface of the Anisian transgression. **C.** Transition between the TST fine grained, dark limestones (*Gg* – Upper Gogolin Beds) and the HST shallowing upward calcarenites (*Gr* – Góraždže Beds) of the An 2 sequence. Strzelce Opolskie Quarry. The outcrop is 10 m high. **D.** Sequence boundary (*SB*) of the An 3 depositional sequence in Upper Silesia. The boundary is uneven surface of the calcarenitic shoals of the Góraždže Beds. The sharp contact between the calcarenites and the slumped, unfossiliferous, lime muds (*Sl*) suggests a tectonically-controlled drowning of the basin floor. *HB* – Haupterinoidenbank. Góraždže Quarry. **E.** Detail of the slumped horizon from Fig. 11D. Św. Anna Hill. Upper Silesia. **F.** Storm wave ripplemarks featuring the top of the Haupterinoidenbank. The amplitude of the ripplemarks (1–1.5 m) suggests the water depth below 20 meters. Góraždže Quarry. **G.** Section of the uppermost part of the Góraždže Beds (*Gr*) and the Terebratula Beds (*Tr*). B 1, B 2 and B 3 – position of the brachiopod specimen sampled for the stable isotope procedure applied in the paleobathymetric estimation. See text for discussion. *sb* – boundary of the sequence An 3, *mfs* – maximum flooding surface of the sequence An 3

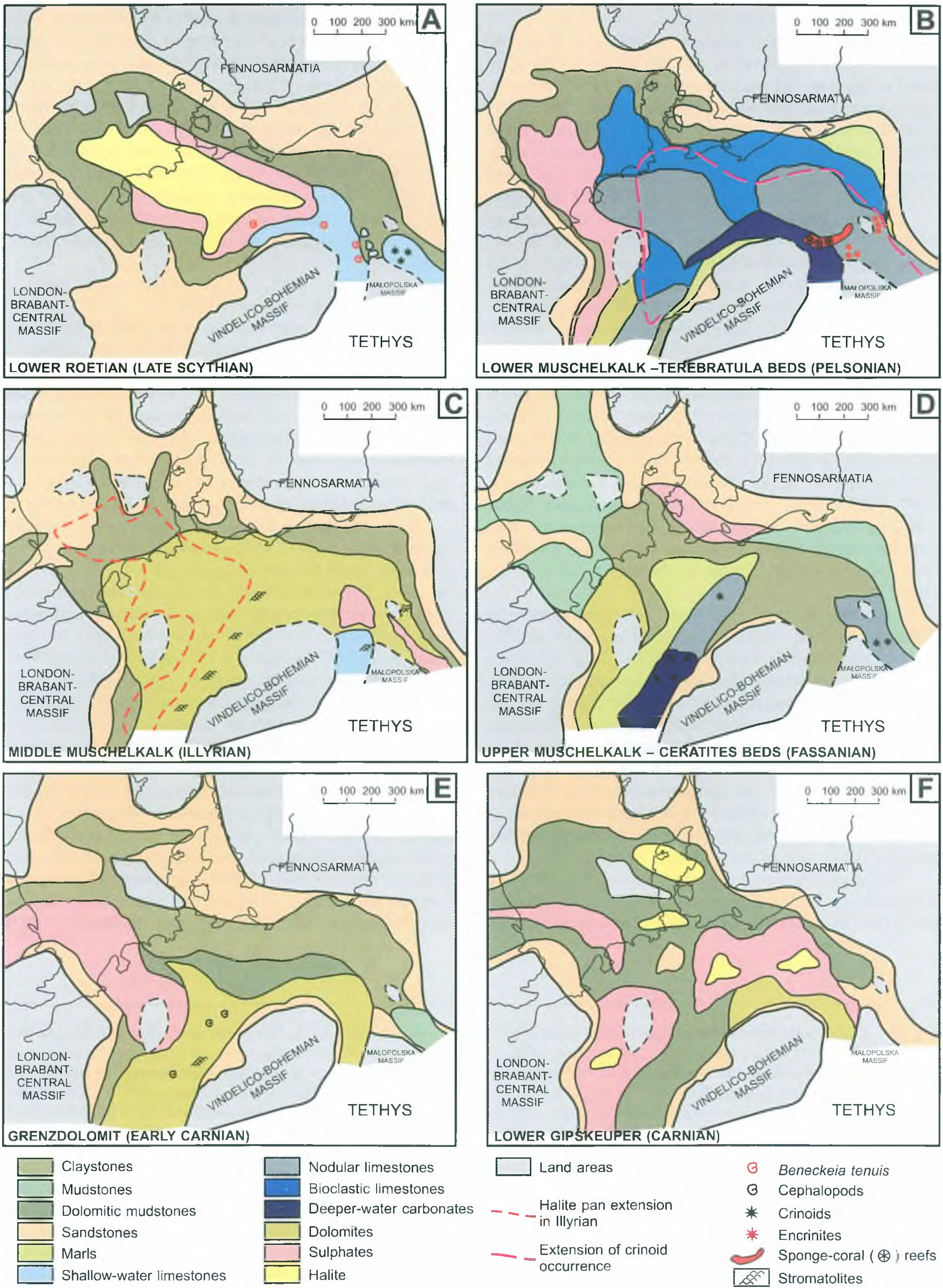

A
0 100 200 300 km
FENNOSARMATIA
LONDON-BRABANT-CENTRAL MASSIF
VINDELICO-BOHEMIAN MASSIF
MAŁOPOLSKA MASSIF
TETHYS
LOWER ROETIAN (LATE SCYTHIAN)
B
0 100 200 300 km
FENNOSARMATIA
LONDON-BRABANT-CENTRAL MASSIF
VINDELICO-BOHEMIAN MASSIF
MAŁOPOLSKA MASSIF
TETHYS
LOWER MUSCHELKALK –TEREBRATULA BEDS (PELSONIAN)
C
0 100 200 300 km
FENNOSARMATIA
LONDON-BRABANT-CENTRAL MASSIF
VINDELICO-BOHEMIAN MASSIF
MAŁOPOLSKA MASSIF
TETHYS
MIDDLE MUSCHELKALK (ILLYRIAN)
D
0 100 200 300 km
FENNOSARMATIA
LONDON-BRABANT-CENTRAL MASSIF
VINDELICO-BOHEMIAN MASSIF
MAŁOPOLSKA MASSIF
TETHYS
UPPER MUSCHELKALK – CERATITES BEDS (FASSANIAN)
E
0 100 200 300 km
FENNOSARMATIA
LONDON-BRABANT-CENTRAL MASSIF
VINDELICO-BOHEMIAN MASSIF
MAŁOPOLSKA MASSIF
TETHYS
GRENZDOLOMIT (EARLY CARNIAN)
F
0 100 200 300 km
FENNOSARMATIA
LONDON-BRABANT-CENTRAL MASSIF
VINDELICO-BOHEMIAN MASSIF
MAŁOPOLSKA MASSIF
TETHYS
LOWER GIPSKEUPER (CARNIAN)
Claystones
Mudstones
Dolomitic mudstones
Sandstones
Marls
Shallow-water limestones
Nodular limestones
Bioclastic limestones
Deeper-water carbonates
Dolomites
Sulphates
Halite
Land areas
Halite pan extension in Illyrian
Extension of crinoid occurrence
Beneckeia tenuis
Cephalopods
Crinoids
Encrinites
Sponge-coral (⊛) reefs
Stromatolites

Fig. 13. Sponge-coral knobby bioherms from the Pelsonian reefs of Upper Silesia. Tarnów Opolski Quarry. Note the tightly clustered colonies of the reefbuilders

Such a specific environmental convergence led finally to biological uniformisation over the entire basin as is indicated by a similar composition of fauna from different parts of the basin (see Fig 18).

Basin evolution

According to isopach pattern of the lower Muschelkalk the subsidence center stretched from Upper Silesia to NE Germany (Fig. 14A) and approximately followed the Odra–Hamburg Fault (see Fig. 2). Another subsidence centers were situated in SE Poland (East Carpathian Gate tract) and to the E of Thuringia. The latter center joined obliquely the main subsidence axis giving some "triple junction" structure (Fig. 14). A triangle field situated to the west from the junction point and encompassing the area between western Poland, eastern Thuringia and NE Germany shows a very uniform facies style of the lower Muschelkalk succession, depending on the dominance of shallow water calcarenitic deposits (see Fig. 28) ("Brandenburgian Beds" or Rüdersdorf Formation). This indicates that the "triangle field" was controlled by the stable thermal subsidence keeping in pace with the shallow water carbonate sedimentation.

Several smaller local subsidence centers are also evident from the isopach arrangement (Fig. 14A). These local grabens are interpreted as a result of combined activity of the main faults and halokinetic mobilisation of the underlying Zechstein salt (Szulc, 1999).

MIDDLE MUSCHELKALK

4^{th} *Anisian Sequence (An 4)*

The sequence boundary is clearly marked in the entire basin by subaerial exposure products: paleosols, karstic pavements as well as by playa clastics and evaporites (Szulc, 1999). Ubiquitous sponge-microbial stromatolites along with the succeeding unfossiliferous dolomites represent the LST deposits (Szulc, 1997b).

The TST is represented by dolomites and fossil-poor limestones in Silesia and by sulphates in the other parts of the Germanic Basin. As in the first Scythian sequence also during the discussed transgression, thick rock salt deposits formed in the depocenter (Fig. 12C).

The HST is represented by a succession of sulphates, dolomites and limestones displaying features of subaerial exposure (Rothe, 1993). In SW Germany, these carbonates called as "middle carbonate horizon" divide the evaporitic deposits of the sequence An 4 from the overlying evaporites of the first Ladinian sequence (Fig. 15).

Fig. 12. Paleofacies maps for the chosen intervals of the late Scythian–Carnian times of the Germanic Basin. **A.** Paleofacies map of the Germanic Basin during the maximum flooding event of the first late Scythian depositional sequence (S 1). Lower Röt. **B.** Paleofacies map of the Germanic Basin during the maximum flooding event of the third Anisian depositional sequence (An 3). Terebratula Beds. **C.** Paleofacies map of the Germanic Basin during the late highstand of the third Anisian depositional sequence (An 3). **D.** Paleofacies map of the Germanic Basin during the maximum flooding stage of the first Ladinian depositional sequence (*cycloides* – Bank), Fassanian. Dashed line marks extent of *Coenothyris cycloides* (after Hagdorn & Simon, 1993 and Senkowiczowa & Popiel-Barczyk, 1993). Occurrence of crinoids delineates the normal marine milieu. **E.** Paleofacies map of the Germanic Basin during the maximum flooding stage of the La 3 depositional sequence (early Carnian). **F.** Paleofacies map of the Germanic Basin during the highstand stage of the La 3 depositional sequence. Lands outline partly taken from Ziegler (1990)

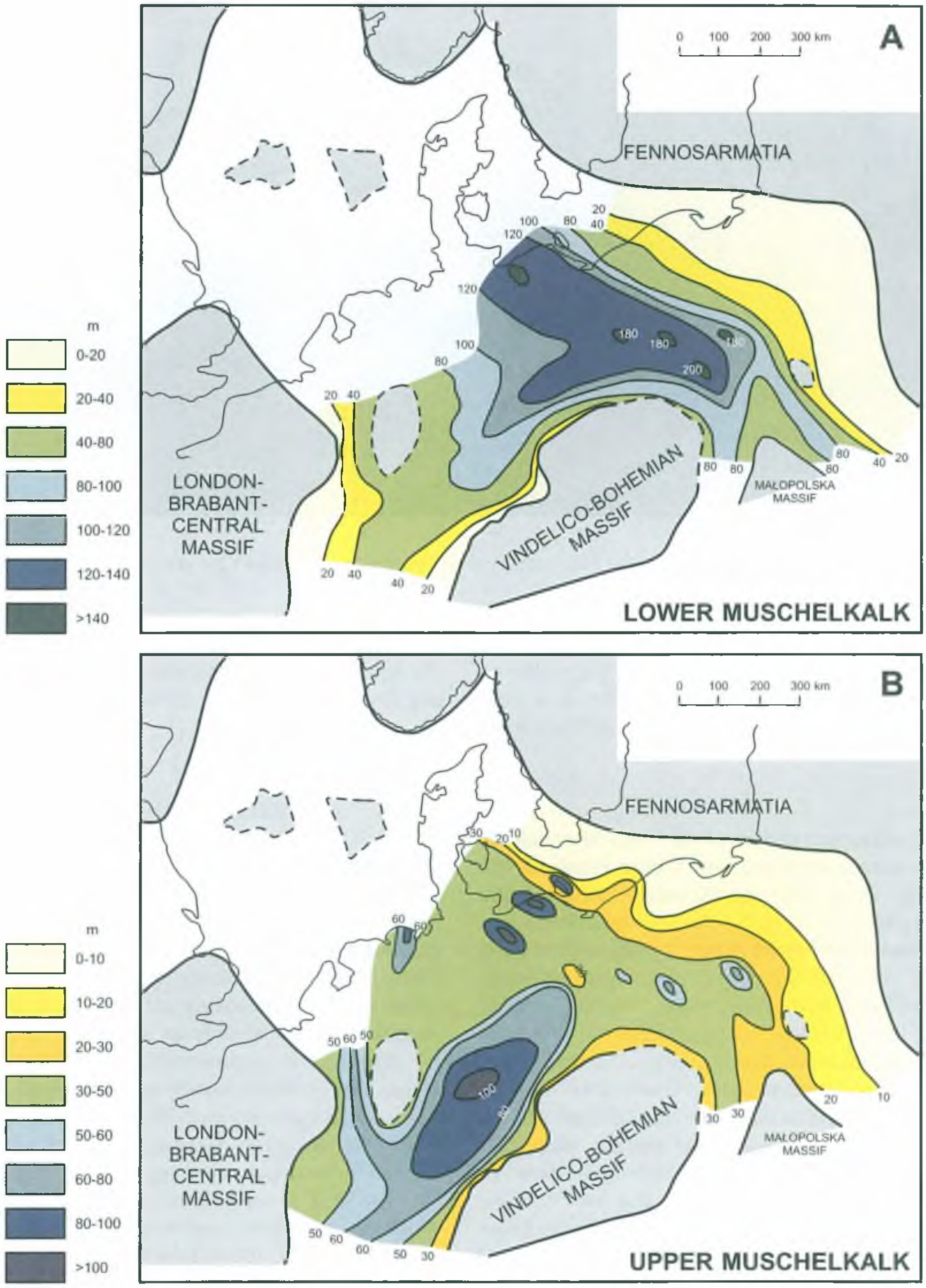


Fig. 14. Isopach maps of the Middle Triassic sediments in the southern and central parts of the Geermanic Basin. **A.** Lower Muschelkalk, **B.** Upper Muschelkalk

Basin evolution

During the Illyrian (middle Muschelkalk), the Germanic Basin underwent structural reconstruction. The subsidence center moved to the intensively subsiding Swabian-Hessian Depression. The Tethys waters overstepped disintegrated Vindelician treshold and accumulated in this depression forming a new depocenter of the Germanic Basin (Fig. 12C). The depocenter was filled up by halite deposits and merged with sulphate-dolomitic sediments toward the basin margins. As indicated by marine carbonate sedimentation in southern Poland, the Silesian and East Carpathian Gates still maintained the communication with the Tethys Ocean. Concurrently in northern Germany, deep but local grabens started to form as ensuing phenomenon of the North Atlantic extension (Szulc, 1999).

UPPER MUSCHELKALK–LOWER GIPSKEUPER

1 st Ladinian Sequence (La 1)

The sequence boundary in SW Germany is formed by the mentioned “middle carbonate horizon” (Rothe, 1993; Friedel & Schweizer, 1988) and by paleosol and karstic horizon in southern Poland (Szulc, 1999).

The LST is represented by evaporites and dolomites in the western basin and by dolomitic limestones in southern Poland.

The TST in the entire western part of the basin is composed of bioclastic or oolitic thick bedded limestones (Trochitenkalk, Glaukonitkalk). In the eastern basin the TST is built by coquina deposits (Pecten discites Beds in the Holy Cross Mts.) and condensed limestones (Wilkowice Beds in Silesia).

Deep ramp marls and limestones of the Hauptmuschelkalk belong to the HST in the German Basin. The maximum flooding surface of the Ladinian in the Germanic Basin is marked by the horizon with *Coenothyris cycloides* (“*cycloides*-Bank”) (Aigner & Bachmann, 1992) occurring from the Holy Cross Mts. to SW Germany (Fig. 12D). The Hauptmuschelkalk deposits were succeeded by prograding shallow marine limestones and dolomites representing the late highstand stage (Aigner, 1985). To the east and north of Germany, the basin became more and more brackish and the limestones are replaced by marls and clastic marine deposits (Figs. 12D, 16). Carbonate sedimentation persisted in the Holy Cross Mts. where the Ceratites Beds evidence open communication with the Tethys *via* the East Carpathian Gate.

The biostratigraphical data (see below) indicate that in the Polish Basin the normal marine conditions have been replaced by brackish environments with the 4th conodont zone (*Neogondolella haslachensis*), i.e. 3 zones earlier than in the southwestern Germany (Kozur, 1974; Trammer, 1975; Zawidzka,1975). The end of the normal marine sedimentation in the Polish Basin was coincident with the *cycloides*-Bank, i.e. with the maximum flooding phase of the sequence. Nonetheless, despite of the environmental changes, the HST continued up to the lower Keuper in terms of the sequence stratigraphy. An impoverished marine fauna (including conodonts) which occurs in deposits ascribed to the lower Keuper (Lettenkeuper) (Assmann, 1926; Gajewska,

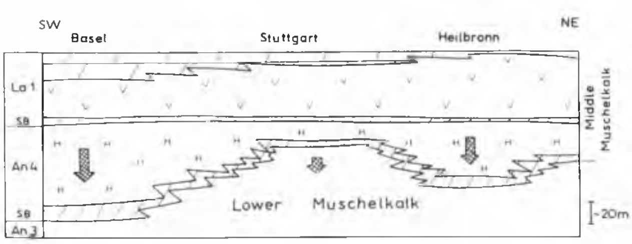


Fig. 15. Facies pattern, depositional sequences and the interpreted subsidence intensity (arrows) of the Middle Muschelkalk between Basel (Switzerland) and Lower Franconia (SW Germany). The minimum subsidence upon the Swabian treshold. Baased on data by Geyer and Gwinner (1986). H – halite, V – sulphates, obliquely hatched – dolomites. SB – sequence boundary. Modified from Szulc (1999)

1978; Narkiewicz, 1999) supports the presumption.

The biostratigraphic data, (including the palynostratigraphical data, Orłowska-Zwolińska, 1983) suggest that the lower-middle Lettenkeuper (lower and middle Sulechów Beds) of the Polish Basin are of Longobardian age, i.e. they correspond to the upper Hauptmuschelkalk in southwestern Germany. All the above mentioned biostratigraphical conclusions are confirmed by the magnetostratigraphic data (Nawrocki & Szulc, 2000).

Basin evolution

As the isopach pattern shows (Fig. 14B) the subsidence center moved definitely to the Swabian-Hessian Depression where the upper Muschelkalk attains 100 m in thickness, i.e. 2–3 times more than in the Polish Basin.

Lithofacies distribution and fauna assemblages indicate that the Germanic Basin communicated with the Tethys Ocean by the Western Gate. The Silesian Gate became restricted in the uppermost Muschelkalk while the open communication persisted through the East Carpathian Gate. This is convincingly illustrated by the crinoid distribution (Fig. 12D).

Shallowing trend and clastic sedimentation in the Polish Basin was involved by the intensive crustal uplift which experienced the eastern basin already by the end of Fassanian time (Fig. 16; Szulc, 1999). The transition between the downwarp regime dominating in Anisian time and the uplift phase of the Ladinian has been expressed in form of a basinwide condensation event which took place in mid-Fassanian time (Trammer, 1975; Zawidzka, 1975).

2 nd Ladinian Sequence (La 2)

Tectonically-forced, regional angular unconformity marks the sequence boundary (Aigner & Bachmann, 1992). Regarding however, the earlier uplift of the eastern basin an alternative (older) sequence boundary could be proposed too (see Fig. 17). Marine fine clastics and dolomites, affected by submarine condensation phenomenon represent the TST and HST in SW Germany (Aigner & Bachmann, 1992). The marine deposits pass into the brackish and deltaic clastic sediments of northeastern Germany and northern Poland. Farther to the north and east these onshore facies grade into continental mudflat deposits (Fig. 16B; Szulc, 1999).

A limited communication with the Tethys existed exclusively *via* the Western Gate. Because of the uplift of the Vindelico-Bohemian Massif, the eastern gates were closed. The southern Poland area was emerged and the incised valleys system developed.

3 rd Ladinian Sequence (La 3)

The emersion continued in southern Poland during the next cycle hence it is not possible there to decipher the boundary between the La 2 and La 3 depositional sequences (Fig. 16).

In the German area the sequence boundary is outlined by the incised valley system resulted from braided streams activity (Aigner & Bachmann, 1992). The sequence boundary is accentuated by palynologically barren redbeds succession (Orłowska-Zwolińska, 1983) extremely impover-

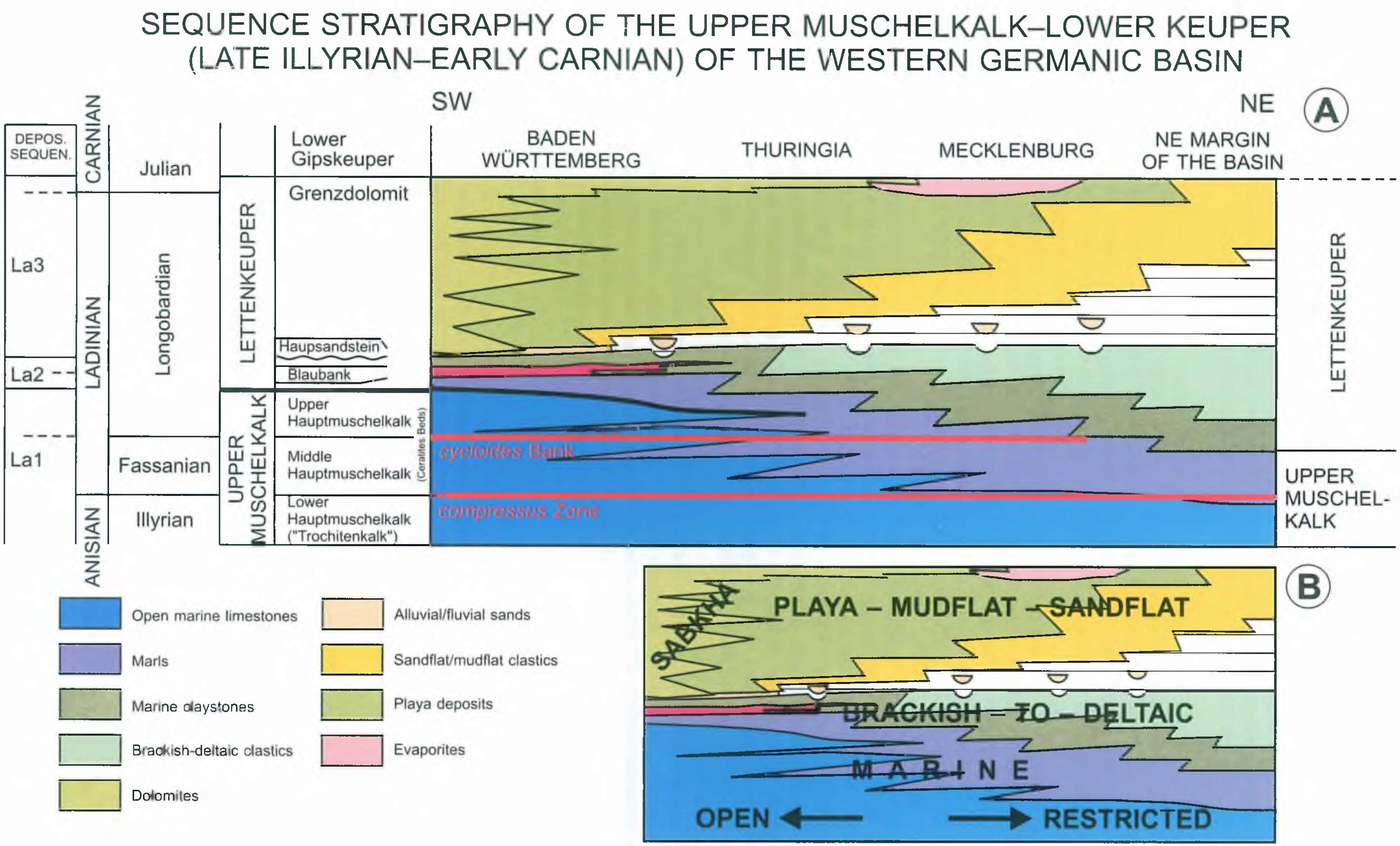


Fig. 16. **A.** Sequence stratigraphic framework of the upper Muschelkalk – lower Keuper deposits in the western Germanic Basin. Heavy line between the upper Muschelkalk and Lettenkeuper marks the regional angular unconformity in SW Germany; **B.** Environmental interpretation of the lithofacies distribution from Fig. A

ished in faunal fossils (Gajewska, 1978).

Fluvial deposits (so called Hauptsandstein complex) filling the incised valley system represent the LST deposits (Aigner & Bachmann, 1989). Lithological and geochemical properties of the fluvial clastics indicate the Scandinavian Land as a main source area (Paul & Ahrendt, 1998).

The subsequent TST is represented by marine fine clastics in the central parts of the basin and by carbonates (mostly dolomites) in nearby areas of the Western and Silesian-Moravian Gates (Fig. 12E). During the maximum flooding phase (Grenzdolomit), the transgression attained an extent similar as in the upper Muschelkalk (Figs. 12E, 16). During this time, nektonic ammonoids migrated through the Western Gate reaching Thuringia (Müller, 1970) and a rich assemblage of pelecypods and gastropods wandered *via* the Silesian Gate (Assmann, 1926).

The HST deposits are mostly playa evaporites and mudflat clastics of the lower Gipskeuper which displays uniform thickness and facies distribution over the whole basin (Fig. 12F).

Basin evolution during the La 2 and La 3 Sequences

The crustal uplift which began in the eastern basin already in Fassanian time encompassed finally the entire northern Peri-Tethys area and the Germanic Basin was featured by braided streams activity. The East Carpathian Gate became closed and limited communication with the Tethys existed through the Western Gate and by the Silesian-Moravian Gate (in the latter only about the maximum phase of the transgression).

Synsedimentary tectonism lessened, with except of the North Atlantic domain (North Sea, northern Germany (Frisch & Kockel, 1998) and thus the basin filled up and its relief became relatively low.

Only during the later Carnian, a tectonically controlled topographical rejuvenation and climate pluvialisation resulted in a vigorous fluvial activity and clastic sedimentation (Schilfsandstein) over the whole area of the northern Peri-Tethys.

EUSTATIC VS. TECTONIC CONTROLS OF THE DEPOSITIONAL SEQUENCES IN THE GERMANIC BASIN

In order to decipher the eustatic, tectonic and climatic controls on the third order despositional sequences in the Germanic Basin, I have correlated the sequence stratigraphic framework with other basins from the western Tethys domain as well as with the global changes compiled by Haq *et al.* (1987). An attempt of such a correlation has been already made for the Northern Calcareous Alps and Dolomites by Rüffer and Zühlke (1995).

As implied from the correlation setting (Fig. 17) the Germanic sequence stratigraphic framework is generally concordant with other western Tethys basins. It concerns in particular the late Scythian–Anisian sequences which display a close parallelism both with the Southern and Northern Alps. The small shifts between the relevant sequences could be either aftermath of a local tectonic subsidence or can result from still vague correlation of the biostratigraphical subdivisions of the compared basins. More significant differences are featuring the middle and upper Muschelkalk intervals (late Illyrian–Fassanian). The An 4 and La 1 sequences erected on the database from the western (German) basin display an individual character suggesting a strong influence of local tectonic controls. This inference agrees with statements by Rüffer and Zühlke (1995), who recognised a slackening of global, eustatic fluctuations in time under discussion. They have regarded the changes in basin dynamics as resulted from local tectonics. An intensive concurrent tectonic activity has been also recorded in many other basins within the western Tethys domain (Brandner, 1984; Martini *et al.*, 1986; De Zanche *et al.*, 1992; Krainer & Lutz, 1995; Budai & Haas, 1997; Budurov & Zagorchev, 1998).

It seems that also the next sequences (i.e. La 2 and La 3) in the Germanic Basin are bearing a strong overprint of local tectonics. Similar phenomenon has been observed in the Ladinian–Carnian succession of the Northern Calcareous Alps (Rüffer & Bechstädt, 1998). It must be stressed, however, that though the individual sequences do not correlate well, their maximum flooding surfaces display a better coincidence in particular in late Fassanian and early Carnian time (Fig. 17).

In conclusion, the deposition in northern Peri-Tethys area was principally controlled by global sea-level changes, but the eustatic changes were modified by local tectonic controls. The role of the climatic fluctuations (discussed later) was subdued and the climatic factors controlled rather the predominant lithology of the basin fill than involved considerable changes of sedimentary trends in the individual basins.

BASIN EVOLUTION AND BIOTA REACTIONS

From the above presented analysis of the depositional sequences, it appears that the biota evolution in the Germanic province fairly followed the lithofacies succession within the basin. It concerns the faunal diversity, distribution gradients and faunal exchange between the Tethys and Peri-Tethys provinces.

Moreover, the reconstructed migration pathways have been applied as a useful tool for restitution of the paleocirculation pattern in the Germanic Basin. I have also found that significant changes in fauna composition occur at the level of the systems tracts. The changes depend essentially on the various proportion between the immigrants and local species occurring in given systems tracts. The environmental changes such as water depth and energy and oxygenation level became evident after examination of the paleocommunities in terms of their life habit and nutrition way.

A very important attribute of the Germanic Basin is the occurrence of the sponge-microbial stromatolites and the sponge-coral reefs. These buildups give a new insight both for the recovery of the reefbuilders after the P/T extinction and for the paleobiogeographic portrayal of the Middle Triassic.

SEQUENCE STRATIGRAPHY OF NORTHERN CALCAREOUS ALPS, DOLOMITES AND GERMANIC BASIN COMPARISON FOR LATE SCYTHIAN–EARLY CARNIAN TIME

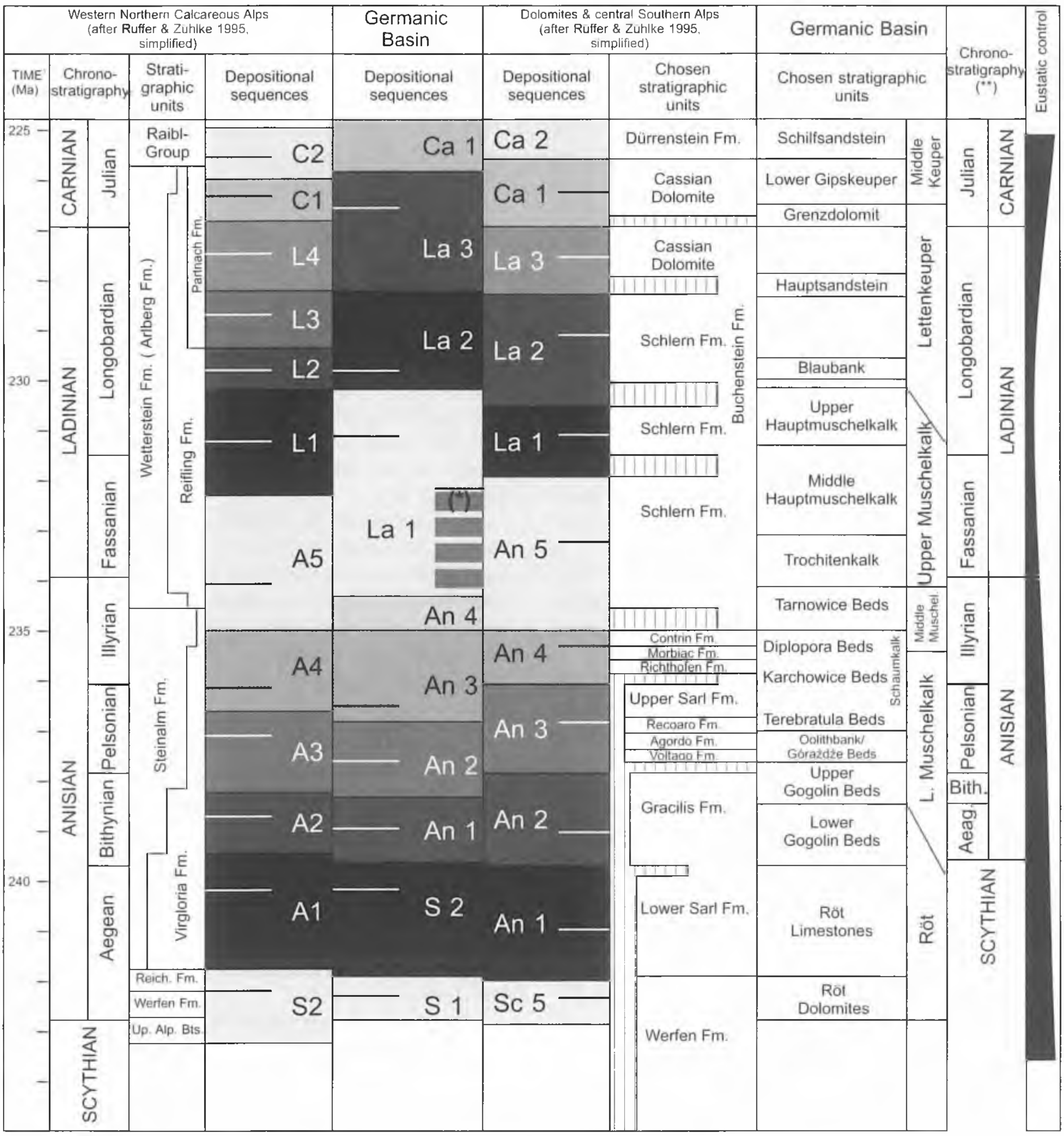


Fig. 17. Comparative setting of the 3[rd] order depositional sequences from the western Tethys and northern Peri-Tethys basins. (*) – an alternative depositional sequence erected for the Polish Basin. (**) – chronostratigraphy for the Anisian–early Ladinian interval in the Germanic basin as inferred from the recent magnetostratigraphic study (Nawrocki & Szulc, 2000). [1] – time scale after Gradstein *et al.*, (1995). See also text for further explanations and comments to Fig. 28

DEPOSITIONAL SEQUENCES AND BIOTA RECORDS

From the fauna composition and diversity of the Anisian sequences in Upper Silesia we can learn the tight reliance between the structure of the community and the type of systems tracts (Fig. 18). The tethyan immigrants dominated always in transgressive systems tracts while their contribution decreases substantially in higstand systems tracts. This phenomenon is particularly visible for the two coupled TST-HST successions of the lower Muschelkalk from Silesia, represented the Upper Gogolin Beds (TST) – Góraždže

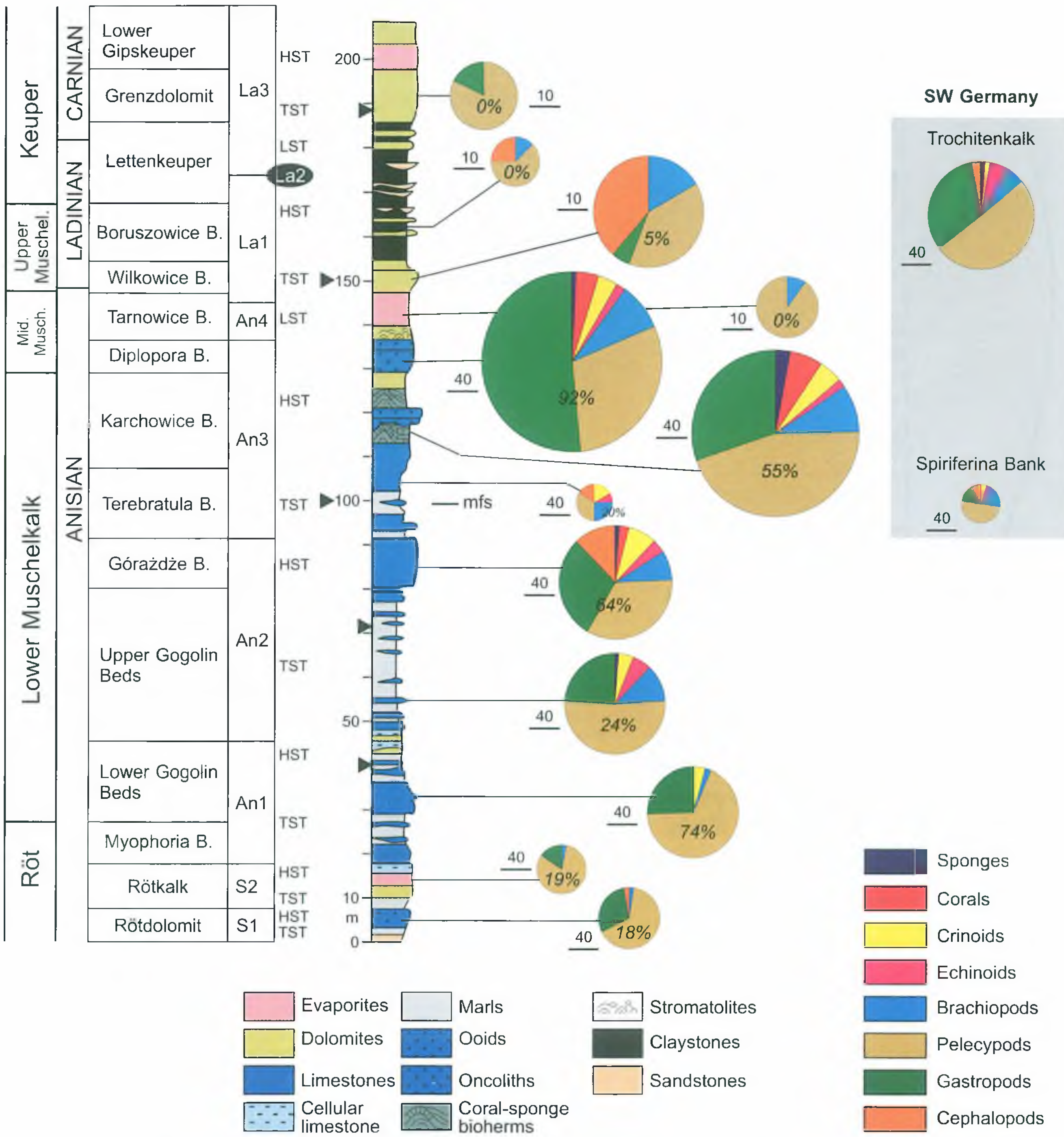


Fig. 18. Diversity (species number) of the invertebrate paleocommunities of the Silesian Basin in relation to the late Scythian–Carnian depositional sequences. The radius length visualises the species number: 40 species for the Anisian interval and 10 species for the Ladinian–Carnian interval. In % – contribution of the local species (partly after Hagdorn and Głuchowski, 1993). The diagrammes for SW Germany elaborated after the data by Hagdorn & Ockert, (1993) and Ockert (1993). Note the lack of the sequence La 2, resulted from nondeposition period between the middle Lettenkeuper and Grenzdolomit in Silesia. See also text for farther discussion

Beds (HST) and the Terebratula Beds (TST) – Karchowice Beds (HST) (Fig.18). This rule is confirmed also by a high proportion of the immigrants featuring the first Scythian sequence (S 1) displaying relatively long TST and short (tectonically shortened) HST. On the other hand, long-lasting LST with dominant, restricted conditions, succeeded by short TST and HST may involve a similar ecological aftermath (cf. e.g. the sequence S 2).

By contrast, the fauna diversity is always much higher for the higstand systems tracts than for the transgressive systems tracts.

The outlined faunal changes reflect the biota response to ecological pressure. The environmental parameters (energy, depth, light and oxygen supply) changed rapidly during the transgression hence the biota could not accommodate to the mutable environmental conditions. Eventually

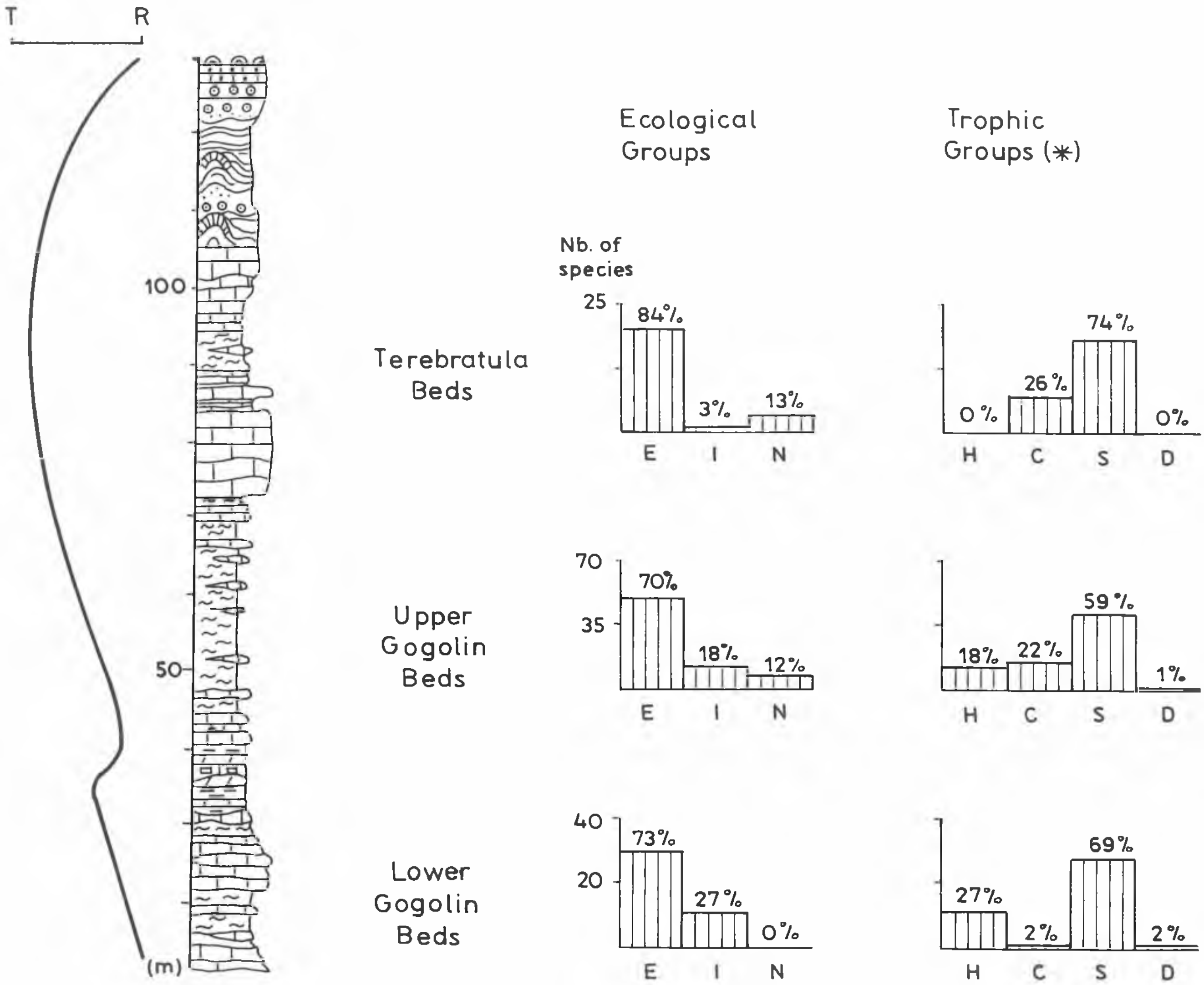


Fig. 19. Changes in paleoecological and trophic groups within the lower Muschelkalk transgressive deposits of Upper Silesia. After own data and data by Rojek (1996). E – epifauna, I – infauna, N – nekton, H – herbivores, C – carnivores, S – suspension feeders, D – sediment feeders. T-R – transgressive-regressive trends. * The analysis concerns only the body fossils

the population became impoverished in species number and dominated by immigrant elements. During the highstand (or stillstand) the environmental conditions stabilised and the fauna became more diversified and rich in species number. The main mechanism of this enrichment was a speciation of local species. The discussed relationship is particularly well documented for echinoderms (Hagdorn & Głuchowski, 1993).

Other explanation is needed for the domination of Alpine elements within the generally impoverished assemblages of the upper Muschelkalk in the Upper Silesian subbasin (sequence La 1) (Fig.18). This phenomenon could reflect conditions unfavourable for biota speciation (e.g. brackish influx and/or clastic dilution) but sufficient to some specialists or conformists which could withstand in such a milieu.

The paleoecological analysis of the evolution of the faunal community may yield additional data useful in reconstruction of the basin dynamics and in better resolution of the depositional sequences. A analysis of some chosen aspects of the lower Muschelkalk communities from Upper Silesia elucidated close relationships between the basin evolution and the faunal response. Three intervals representing the early, advanced, and maximum stages of the Anisian transgression (the Lower Gogolin Beds, the Upper Gogolin Beds and the Terebratula Beds, respectively) have been examined in terms of the basic changes of their paleocommunities. It becomes obvious from the presented data (Fig. 19) that variations in the life habitat follow the cardinal changes in energy and oxygen levels within the water column. The increasing contribution of the nektonic forms (from 0% to 18%) fairly follows the deepening trend, while the decline of the infaunal benthos (from 27% to 3%) and the relative growth of the epifaunal group evidence an acute oxygen deficiency at the sediment/water interface during the maximum flooding stage. This inference about anoxic/dysoxic milieu is supported by a complete recede of skeletal infaunal organisms in some short intervals within the Terebratula Beds.

The decline of herbivores population (up to 0% in Terebratula Beds) apparently reflects the deepening below the photic zone during the maximum flooding interval. The decline of herbivores goes in hand with changes in deposit-feeders contribution and with the ichnofabric indices (see chapter on trace fossils). Relative increase of suspension-feeders fairly indicates the lower energy level of the benthic habitat and it is consistent with the above discussed variation in the other trophic groups.

TETHYAN FAUNAS IN GERMANIC BASIN AND THEIR PROVENANCE

The answer for the question where the tethyan fauna in the Germanic Basin came from, is controversial to date. In contrast to thoroughly analysed and synthesised data on biota from the Germanic Basin, the studies on the Alpine fauna distribution and paleobiogeography are dispersed and lacking any modern integrating synthesis.

Nevertheless we can get some general pattern of the migration history by the analysis of the peritethyan faunal composition during Middle Triassic time.

The late Scythian and early Anisian (Aegean) the fauna assemblages from southern Poland (in particular from the Holy Cross Mts.) display an affinity to the Paleo-Tethys (Asian province) and the eastern Neo-Tethys basins (Parnes, 1965; Głazek *et al.*, 1973; Gaździcki *et al.*, 1975; Trammer, 1975, 1979; Mostler, 1993).

During Pelsonian time, the eastern Neo-Tethys seaway along with the mid-Neo-Tethys (southern Alpine basins) became the most important migration centers for the Muschelkalk faunal community (Buch, 1849; Mojsisovics, 1882; Bukowski, 1895; Assmann, 1937; Mostler, 1993; Hagdorn & Głuchowski, 1993; Hagdorn, 1996 a, b; Hagdorn *et al.*, 1996). The affinity between the Upper Silesian Muschelkalk and the southern Alpine province is particularly well visible for the fauna of the Pelsonian maximum transgression stage (Terebratula Beds in Upper Silesia, Recoaro Formation in the Southern Alps) (Bechstädt & Brandner, 1970; De Zanche *et al.*, 1992; Hagdorn & Głuchowski, 1993; Hagdorn *et al.*, 1996; Brack *et al.*, 1999). Moreover, the contemporary faunal community occurring in the Transdanubian Range and in the Mecsek Mts. is also very close to the above mentioned regions (Palfy & Török, 1992; Hagdorn *et al.*, 1997; Szente, 1997). This indicates that a free communication existed between all the discussed basins. Furthermore, the fauna affinity between the Upper Silesian Muschelkalk and the Middle Triassic of the Mecsek Mts. corresponds to a strikingly similar sedimentary evolution of the both basins (Török, 1997). It suggests, in turn, their close paleogeographical position and cognate structural evolution during Anisian–Ladinian times.

In conclusion, regarding the fauna migration in Anisian time, the most probable communication pathway between the Germanic Basin and the Tethys Ocean led through the spreading belt of the Neo-Tethys rift dividing the Adria Plate and the Rhodopes-Tisia Plates (see Fig 1). The submeridionally running spreading center continued northward and joined the Silesia area throughout the reactivated Silesian-Moravian fault (see Fig.1).

Since the austroalpine basins were dominated in Anisian time by unfavourable restricted conditions (Reichenhaller Beds, Gutenstein Beds) the faunal development was limited. Therefore the austroalpine faunal elements are sparsely represented in the Anisian deposits of the Germanic Basin. Their contribution in biota communities increased only in Ladinian time when the western connection became open (Hagdorn & Simon, 1993). It is also very likely that as suggested by Mostler (1993) the main migration pathway during Ladinian time encompassed the western branch of the Neo-Tethys spreading belt, striking from Sicily toward the Western Gate (see Fig.1).

PELSONIAN REEFS IN THE SILESIAN BASIN AND THEIR PALEOBIOGEOGRAPHICAL AND PALEOBIOLOGICAL IMPLICATIONS

Sea level changes and anatomy of the Silesian reefs

The hitherto recognised buildups occur in a belt stretched from the western Upper Silesia to the western Holy Cross Mts. The belt reaches ca. 150 km in length and 30 km in width (see Fig. 12B). The best developed bioherms are visible in western Upper Silesia where they are the main constituent of the Karchowice Beds. The sponge-coral buildups form patches of some 2–80 meters across and several meters high. The shape of the bioherms changes from small isolated knobs (see Fig. 21C) to 8 m high, complex mounds rising above the surroundings. The mounds have been abraded by storms and yielded detritus to the adjoining intermound depressions (Bodzioch, 1991).

The buildups display a vertical variability of their composition reflecting thus the ecological succession of reef constructors (Fig. 20). This succession is typical for the "catch up reefs" (James & Mcintyre, 1985) affected by the highstand shallowing-upward trend in the basin. Generally, the buildup construction began with prostrate colonies of Hexactinellida sponges which overgrew and stabilised giant subaqual bioclastic dunes moved only by extremely strong storm waving. The sponges formed thin (up to 3 cm) veneers perfectly mimicking disposition of the dune surface (Figs. 21A, 21B). A contribution of the sponge component grows upsection and they form compact and thick (up to 3 m) biostromal fabrics which grade laterally to low-relief buildups. Finally, the biostroms were succeeded by sponge buildups which reached 8 m in height (Bodzioch, 1991). With the further upward growth and relative shallowing, other organisms contributed to reef community: crinoids, other species of sponges, brachiopods, worms and encrusting forams (including *Tubiphytes*) and first of all, the scleractinian branched corals (*Volzeia szulci*). The sponges and *Volzeia* corals form domes and knobs clustered together (see Fig. 13). When the reef crest reached the surf zone, the encrusting corals (*Pamiroseris silesiaca*) constructed crusts typical of highly turbulent environments (Bertling, 1995) which terminate practically the development of the reefs in the Silesian Muschelkalk.

The Silesian buildups show a significant proportion of cryptocrystalline and peloidal carbonate fabrics dominating in the spongean components. The muddy fabrics display characters of typical automicrite produced in a complex

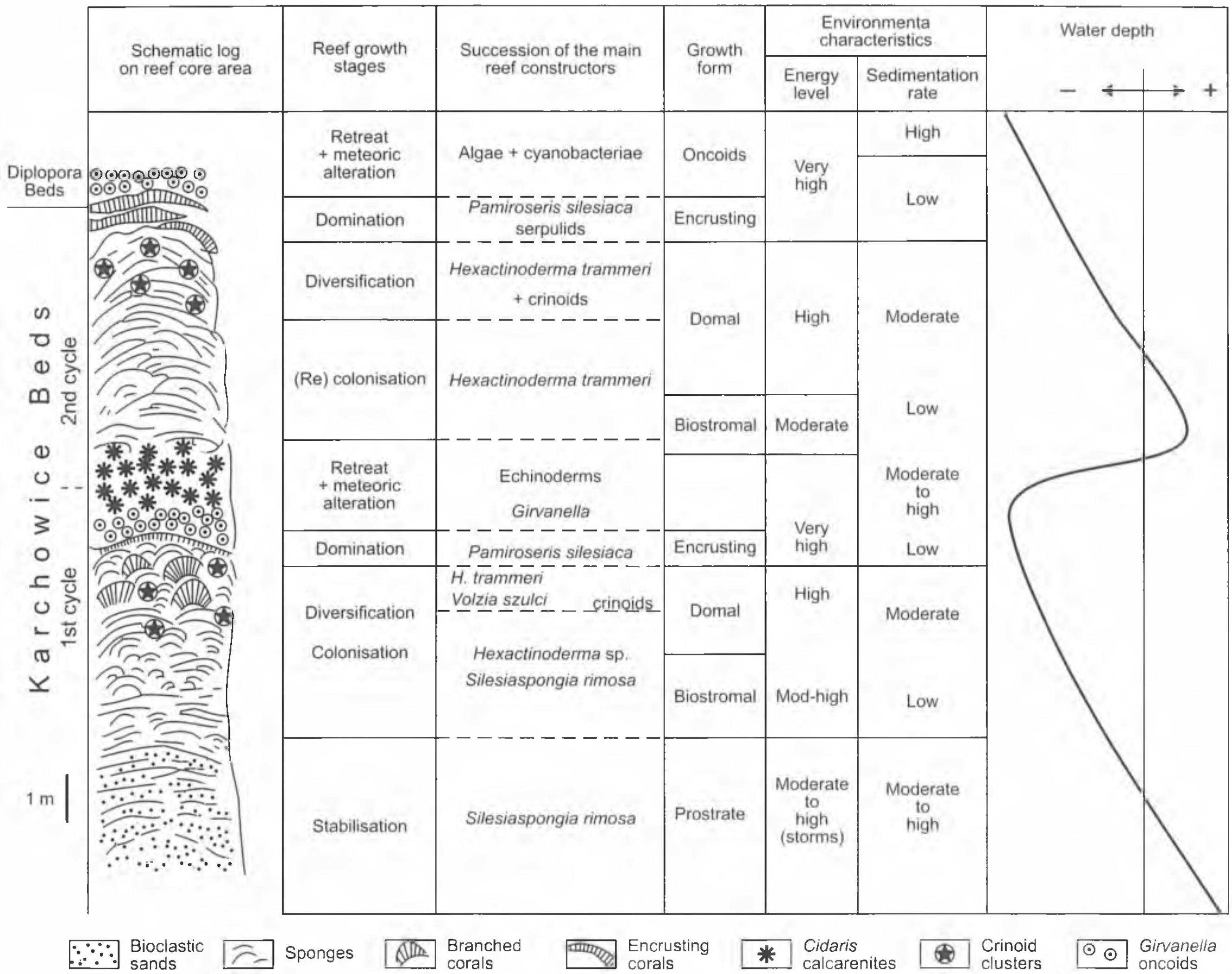


Fig. 20. Reef succession of the sponge-coral buildups of the Karchowice Beds, Pelsonian. Locality – Tarnów Opolski, Upper Silesia. From Hagdorn *et al.* (1999), partly changed. Fauna determination: corals by Morycowa (1988), sponges by Bodzioch (1994)

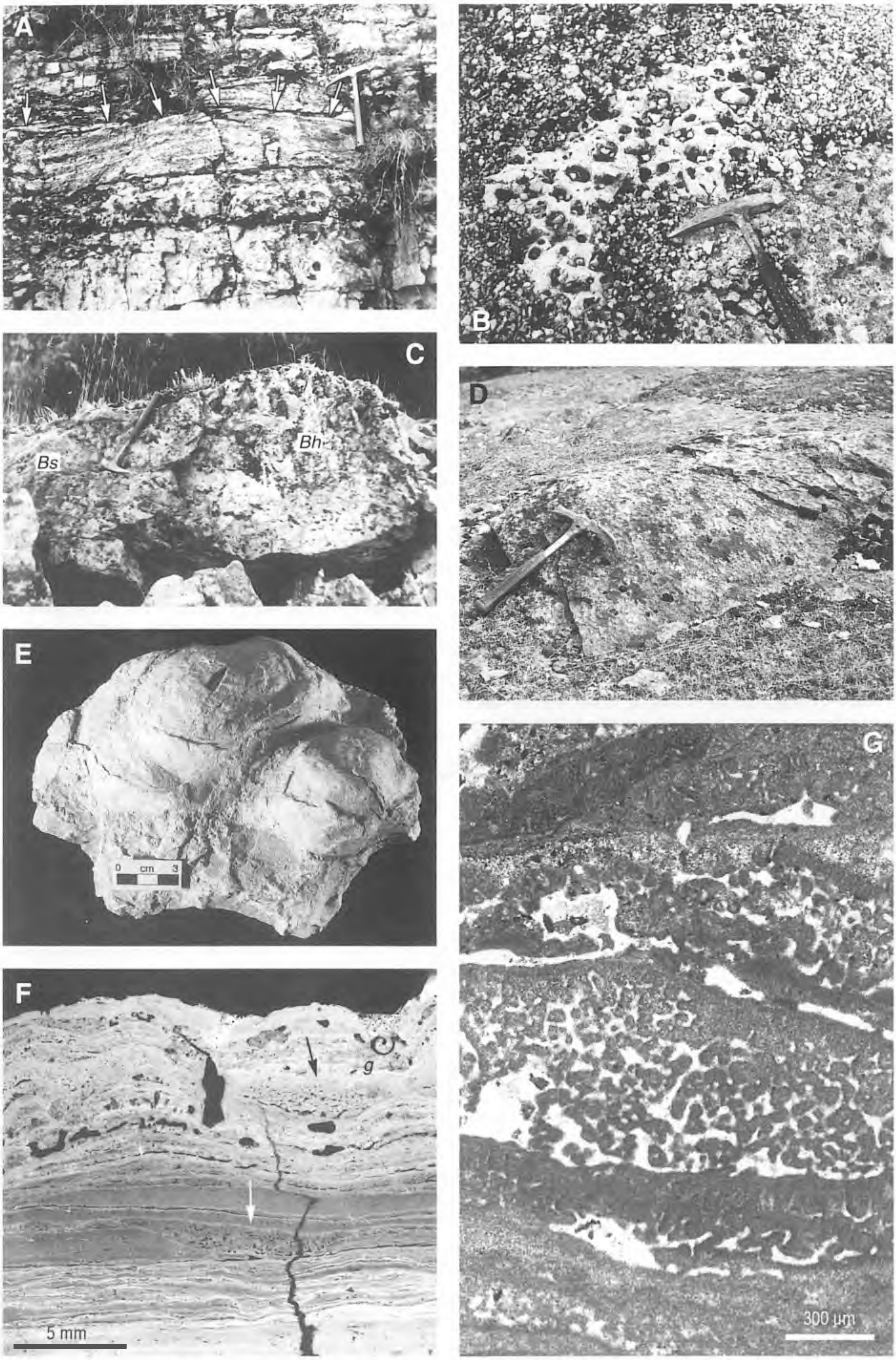
process of bacterially-mediated calcification of sponge bodies (Reitner, 1993).

Paleobiogeographical and evolutionary implications

It must be stressed at first that although the Silesian reefs are one of the oldest *in situ* found Mesozoic reefs in the western tethyan domain, they passed almost unnoticed in the papers dealing with reefs evolution after the P/T crisis (see e.g. Flügel, 1982; Riedel, 1991; Flügel & Flügel-Kahler, 1992). As a matter of fact the Silesian reef complex is the oldest *in situ* preserved Anisian reef known from the western Tethys domain. The another one, is the Illyrian reef community from the Dolomites, described and studied in details by Fois and Gaetani (1984). The other Anisian reefs are either reconstructed after preserved reef debris (e.g. Senowbari-Daryan *et al.*, 1993) or their age is not definite (see the discussion by Stanley, 1988 and by Senowbari-Daryan *et al.*, 1993). Finally, the Anisian "reefs" from the Mecsek Mts. (Kolosvary, 1958) appeared to be diagenetically replaced and deformed molds of selenite crystals (pers. observations).

The incipient Triassic buildups are believed to inhabit deeper and protected settings dominated by muddy substrate (Fois & Gaetani, 1984; Stanley, 1988) but the Silesian reefs differ distinctly both in the energy level and substrate characters. From the earlier outlined sedimentary context

Fig. 21. Sponge and sponge-microbial fabrics of the Muschelkalk. **A.** Bioclastic hummocks stabilised by prostrate colonies of hexactinellid sponges (arrows). Karchowice Beds, Tarnów Opolski Quarry. **B.** Plan view of the prostrate colony from Fig. 21A. **C.** Small sponge bioherm (*Bh*) grading laterally to biostromal form *(Bs)*. Karchowice Beds, Tarnów Opolski Quarry. **D.** Sponge-microbial stromatolite mound developed upon oolitic bar. Middle Muschelkalk, Hardheim, Baden-Württemberg. **E.** Hemispheroidal stromatolite colony. Middle Muschelkalk, Libiąż, Upper Silesia. **F.** Microscopic view of sponge colonies (arrows) interbedded within microbial mat. *g* – spirorbid tube. **G.** Details of the sponge microcolonies. Note the reticulate fabrics and peloidal, automicritic matrix


A
B
C
Bs
Bh
D
E
0 cm 3
F
g
5 mm
G
300 µm

and the reef structural pattern itself, we can learn that the basin was controlled by severe storm wave action. The reefs grew up certainly within the photic zone as is evidenced by early meteoric diagenetic imprints and by *Girvanella* oncoliths succeeding directly the reefs. This in turn implies a possible zooxanthellate algae-coral association, denied hitherto for the early scleractinian corals (cf. e.g. Stanley, 1988).

From the paleobiogeographical point of view, the Silesian reefs belong rather to the circum-tethyan reef belt than to the epicontinental Germanic Basin (cf. fig. 1 by Stanley, 1988).

SPONGE-MICROBIAL STROMATOLITES

Epicontinental Triassic deposits of the northern Peri-Tethys abound in shallow marine stromatolites. It is noteworthy that the term and definition of "stromatolite" has first been introduced by Kalkowsky (1908), for biolaminated fabrics occurring within limestones of the lower Buntsandstein in the Harz area.

Stromatolites are common also in the younger Triassic sediments (Röt and middle Muschelkalk) and they occur from Baden-Württemberg through Thuringia and Silesia to the Holy Cross Mts. in Poland (Fig. 12C). These stromatolites are exceptional since they have been constructed by sponge-microbial community inhabiting extremely shallow, peritidal environment. The sponges are commonly thought to be indicative of deeper, subtidal depths. The Muschelkalk Basin is the first one where sponges have been found in a very shallow setting; the stromatolites occur within emerged oolitic bars or upon exposed karstified horizons and mark the sequence boundary (Szulc, 1997b). The stromatolites are composed of interfingered laminated segments of microbial origin and small (< 0.5 cm) lenticular, spongean bodies (Fig. 21F). They show a variety in morphology ranging between mm-thin flat laminites to 50 cm-thick columnar horizons (Figs. 21D, 21E). As a rule, the thicker, the sponge-richer are the stromatolites.

Because of the animal component, the growth of the Muschelkalk stromatolites was independent on photo- and geotropic controls. For example, in Laibach (Baden-Württemberg) the stromatolites envelope narrow, 1.5 m-deep karstic fissures penetrating oolitic shoals (Hagdorn *et al.*, 1999) and in Upper Silesia they are coating the tepee-hummocks of 1m in height.

A poor preservation of internal structures hinders unequivocal determination of the sponges but the dictyid Hexactinellidea seem to be the main animal constructor of the Triassic stromatolites. In spite of this, the aphanitic and peloidal automicrite carbonate fabrics (Fig. 21G) typical of the spongean-microbial association are recognisable (Reitner, 1993).

According to published descriptions and illustrations of the Carnian stromatolites from evaporitic sequences of Baden-Württemberg (Bachmann & Gwinner, 1971) as well as from several Triassic sections in the western Tethysside (Walther, 1927; Baud, 1987; Spötl, 1988) one may presume that the sponge-microbial stromatolites were commonplace in the shallow water basins of the Triassic. It seems very probable that the Triassic sponge-microbial stromatolites could be a kind of so called "disaster form" (Schubert & Bottjer, 1992) enabling survival and recovery of the sponge buildups after the Permian–Triassic mass extinction event.

MUSCHELKALK DEPOSITIONAL SEQUENCES AND ICHNOFOSSILS RESPONSE

Trace fossils assemblages in the Middle Triassic marine succession of the Upper Silesian Muschelkalk, fairly followed transgressive-regressive trends recorded in carbonate sequences (Szulc, 1990). In the present study, the ichnofabrics (*sensu* Ekdale *et al.*, 1991) are referred against the distinguished systems tracts in the Upper Silesian subbasin (see Fig. 24).

Sequence An 1 (Myophoria Beds–Lower Gogolin Beds)

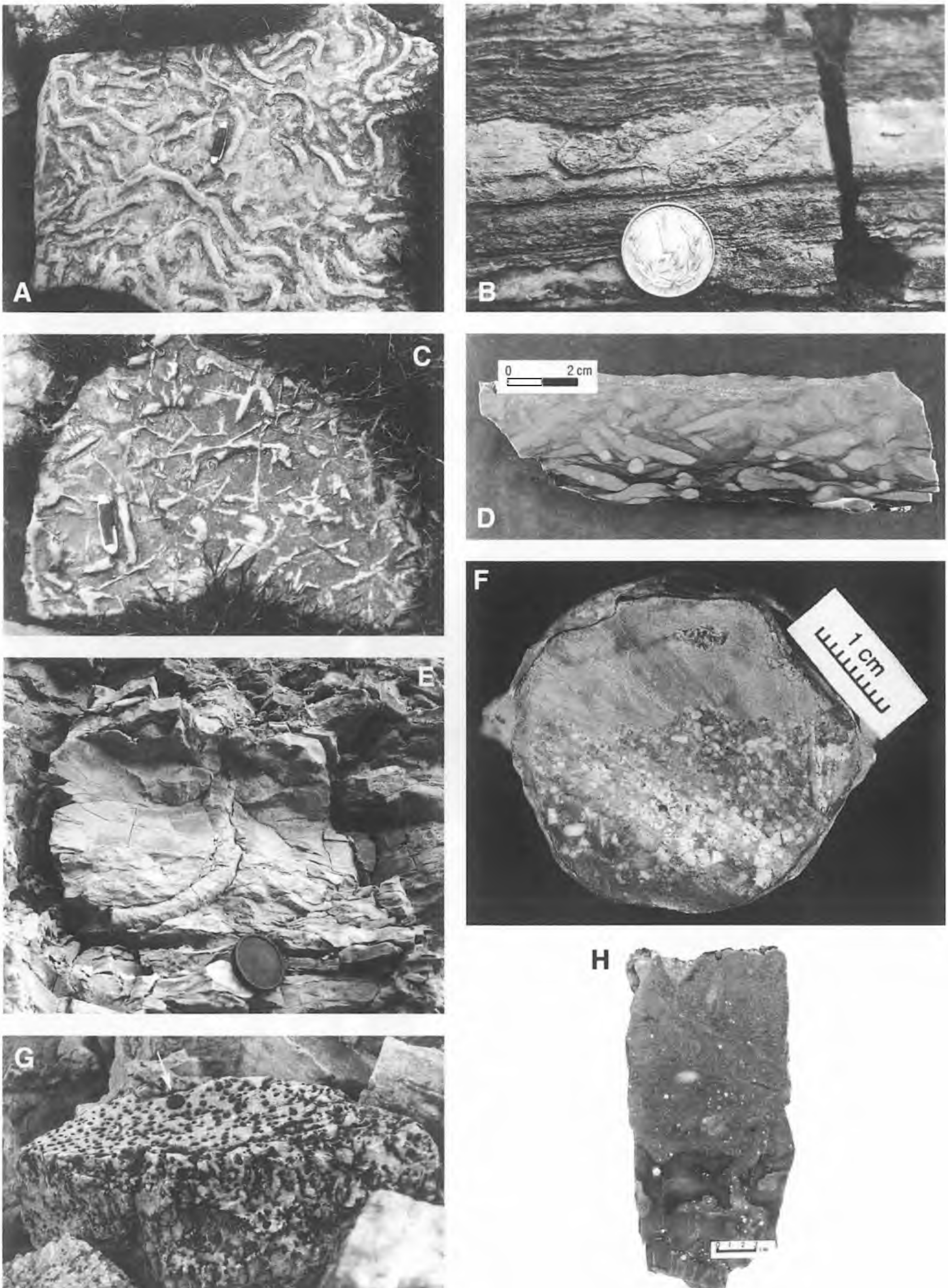
The initial phase of the Muschelkalk transgression is represented by *Rhizocorallium-Teichichnus* ichnofabric dominating within marly sediments of the sequence. These deposits formed in shallow marine, well aerated environments, strongly affected by storm events. A typical lithologic succession of this sequence is composed of alternated marls and bioclastic limestones. The limestone beds formed during storms (tempestites) while the marls deposited during fairweather periods with significant input of a land-derived fine-grained clastics. As a rule the *Rhizocorallium* (Fig. 22A) occur within marl intercalations and they led to a complete disturbation of the host sediments. The traces are less frequent in the limestones and the *Rhizocorallium* isp. are replaced by their (sub)vertical variation called *Teichichnus* ichnofabrics (Fig. 22B). The traces are commonly filled with fecal pellets grouped in spreiten. The *Rhizocorallium-Teichichnus* ichnofabric dominates the entire sequence with except for the omission surface representing the maximum flooding interval of the sequence An 1. This hardground is colonised by *Placunopsis* bioherms which are intensively bored by *Planogloba macrogota* isp. (Fig. 23E).

Other accessory traces accompanying the *Rhizocorallium* are straight stick burrows filled with fecal pellets and called *Planolites* isp (Fig. 22D) or molded with adjacent sediment *Paleophycus* isp. (Fig. 22C).

Sequence An 2 (Upper Gogolin Beds–Górażdże Beds)

The *Rhizocorallium* ichnofabrics which occur in the basal part of the sequence retreat upsection and is replaced by

Fig. 22. The Muschelkalk trace fossils from Silesia. **A.** *Rhizocorallium* isp.; **B.** *Teichichnus* isp. partly eroded by storm action. Coin diameter ca. 1.5 cm; **C.** *Paleophycus* isp. molds; **D.** Cross section of *Planolites* isp.; **E.** *Pholeus* isp.; **F.** Cross section of the *Pholeus* tube filled with graded crinoidal debris.; **G.** *Balanoglossites* isp. burrows. **H.** Cross section of the frimground formed by *Balanoglossites* burrows and covered by tempestite deposits. Camera cap for scale (arrow)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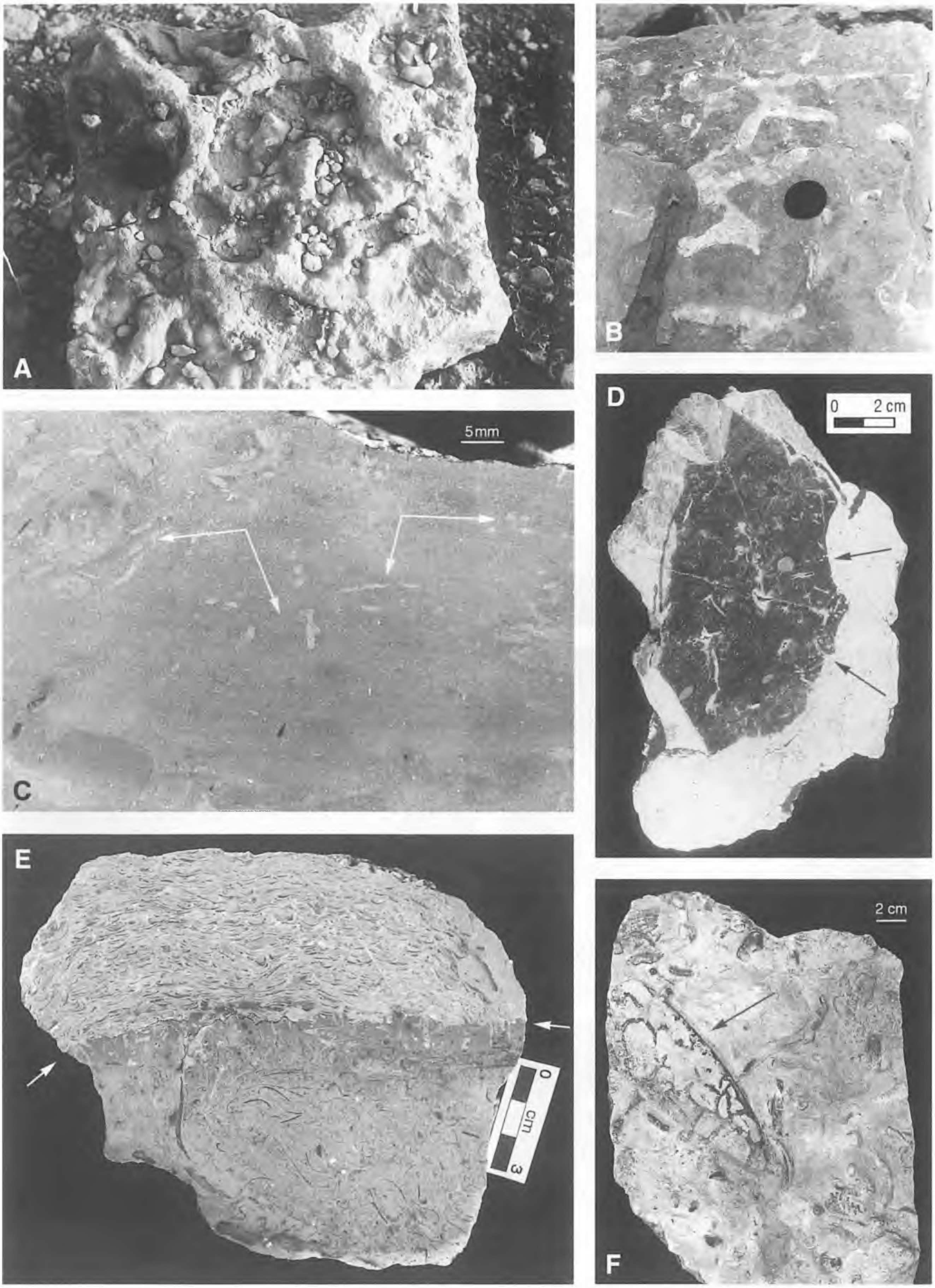
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isolated, subhorizontal U-shaped tubes of *Pholeus isp.* In contrast to the *Rhizocorallium* backfilled burrows, the *Pholeus* tubes were open and reached 2 m in length and 4 cm in diameter (Figs. 22E, 22F). Beside the *Pholeus* traces, the stick burrows of *Planolites* and *Paleophycus* were very ubiquitous during this phase of transgression.

With further deepening, the contribution of *Planolites-Paleophycus* ichnofossils increased and they were accompanied by small branched *Chondrites* traces (Fig. 23C) which could mark the maximum flooding event. Moreover a gradual decrease in burrowing size is observed. As are rule a decrease in trace size indicates a growing deficiency of oxygen in bottom environment (Bromley & Ekdale, 1984).

The succeeding skeletal sand bodies (Górażdże Beds) representing the highstand deposits are featured by vertical, U-shaped open canals of *Balanoglossites* isp. These traces formed firmgrounds horizons and mark the omission interval in sandbar deplacement (Figs. 22G, 22H).

Sequence An 3 (Terebratula Beds–Karchowice Beds–Diplopora Beds).

The sequence boundary is covered by dark to black-coloured muds lacking any bioturbations what evidences anoxic conditions resulted from a very rapid drowning of the basin floor. The subsequent phase of transgression was more moderate however dysoxic conditions dominated as indicated by the very early pyrite-encrustations of the *Cliona* borings piercing the nautiloid shell (Fig. 23F, Szulc, 1990). With gradual oxic amelioration the *Thalassinoides* ichnofabric developed (Fig. 23A). The horizontal, Y-branched passages of *Thalassinoides* ichnofossils, formed complex networks within the Terebratula Beds and a nodular habit of the disturbed sediments. The *Thalassinoides* isp. is accompanied by *Paleophycus* fabric which dominates within bioclastic intercalations. During the highstand phase (Karchowice–Diplopora Beds) the *Thalassinoides* burrows (Fig. 23B) have been joined by *Balanoglossites* fabrics.

Sequence An 4 (Tarnowice Beds–Wilkowice Beds–Boruszowice Beds).

The lowstand, restricted deposits of the sequence (Tarnowice Beds) are devoid of ichnofossils. The subsequent transgressive succession (Wilkowice Beds) comprises *Talpina ruberi* (Fig. 23D) and *Trypanites weisei* borings. This ichnofabric is featuring the basin-wide hardgrounds and stratigraphical condensation interval (Zawidzka, 1975; Trammer, 1975). The overlying, clastic-diluted Boruszowice Beds are poor in trace fossils with except for scarce *Paleophycus* fabrics and sporadic *Cylindricum* isp.

Paleoenvironmental bearing of the Muschelkalk ichnofossils

As shown above the systems tracts of the Muschelkalk sedimentary sequences differ in their ichnofabric composition. The sedimentary sequence of the early transgressive phase of Anisian (An 1) is characterised by *Rhizocorallium-Teichichnus* ichnofabric formed by sediment-feeder organisms (?annelids, crabs; cf. Fürsich, 1974).

The next sequences representing more advanced transgression stages are dominated by suspension-feeders and/or carnivorous organisms (probably the lobster crabs; *Pemphix* sp. found in these sediments (Assmann, 1927; 1944) which have produced the *Pholeus* and/or *Thallasinoides* ichnofabrics. Such a replacement reflects likely the quantity of organic debris available in sediment. The maximum flooding intervals are featured by firmgrounds and hardgrounds with microboring ichnofabrics (An 1, An 4), small-sized *Planolites* and/or *Chondrites* ichnofabric indicating dysaerobic conditions (An 2, An 3).

Typical Muschelkalk highstand deposits (An 2, An 3) comprise *Balanoglossites* ichnofabric produced by enteropneustan worms (Kaźmierczak & Pszczółkowski, 1969).

The clastic-bearing deposits of the HST of the last Muschelkalk sequence (Boruszowice Beds) differ from the precedent ones by overall scarcity of ichnofossils and by appearance of *Cylindricum* ichnofabric reported sofar from the brackish and deltaic Keuper environments (Linck, 1961).

Figure 24 shows the bioturbation index diagram which ranges between 0 to 6, where grade zero describes a lack of bioturbations while grade 6 is referred to a complete bioturbation of the primary sedimentary structures (Taylor *et al.*, 1993).

The ichnofabrics from the lower Muschelkalk of Thuringia (Knaust, 1998) do not differ significantly from the above described Silesian ones. However, a bioturbation intensity as expressed by the bioturbation index (BI) is generally higher for the Silesian Muschelkalk deposits. This indicates obviously a better ventilation of the bottom zone in the Upper Silesian subbasin and it is consistent with other paleoecological indicators (cf. e.g. the benthic fauna diversity).

CARBON AND OXYGEN ISOTOPES EVOLUTION AND Sr-GEOCHEMISTRY IN THE GERMANIC BASIN: PALEOENVIRONMENTAL IMPLICATIONS

It is unnecessary for the purpose of this paper, to review the fundamentals of the stable isotope chemistry in seawa-

Fig. 23. The Muschelkalk trace fossils from Upper Silesia (contd.). **A.** *Thalassinoides* isp. burrows (Terebratula Beds); **B.** Silicified *Thalassinoides* burrows (Karchowice Beds); **C.** *Chondrites* isp.; **D.** Borings of *Talpina* isp. (arrows); **E.** Hardground surface heavily bored by *Planigloba* isp. (arrows) and encrusted by *Placunopsis ostracina* colony. **F.** Polygonal *Cliona* borings (arrow) within the nautoloid shell, encrusted by pyrite

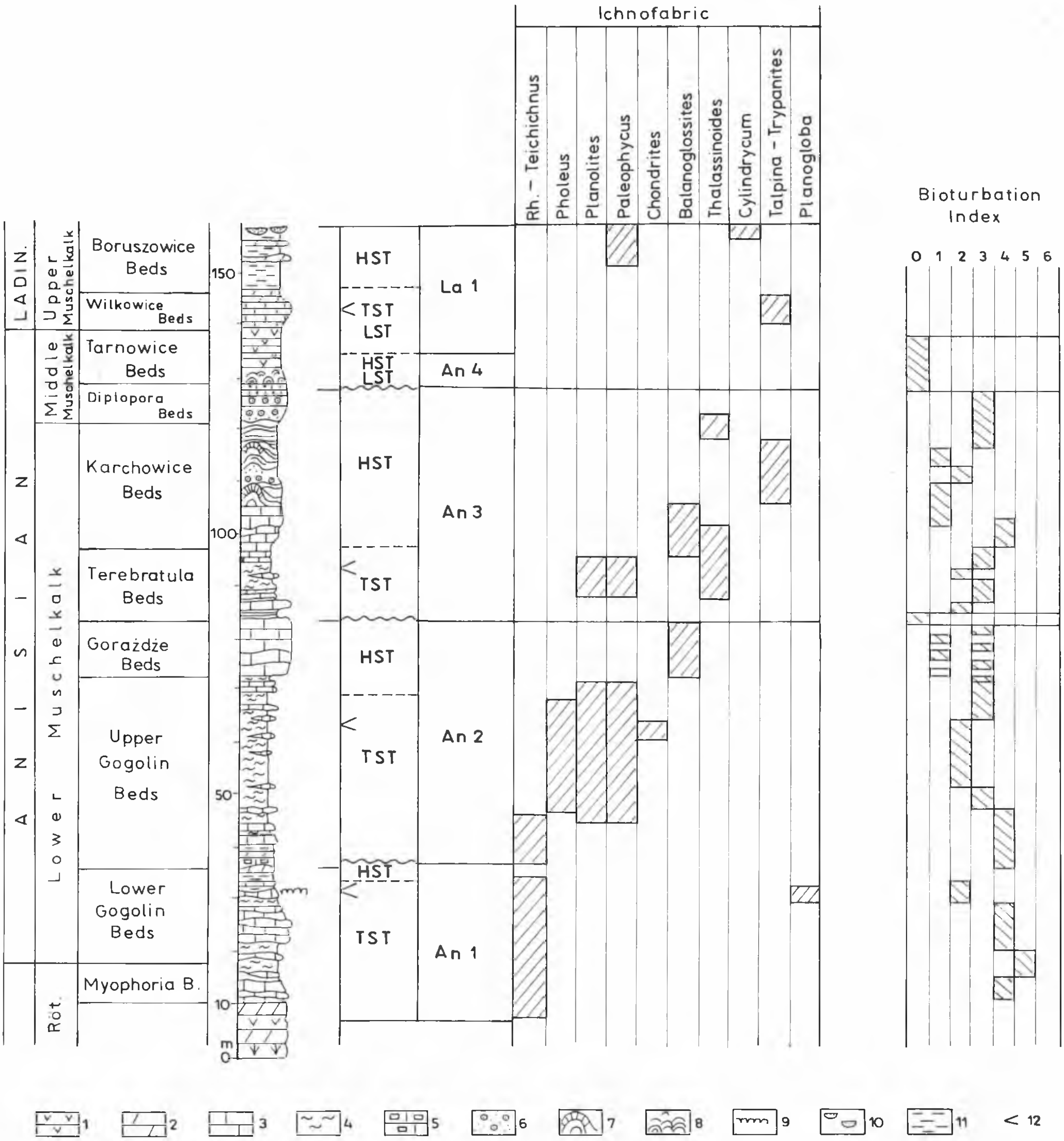

Fig. 24. Ichnofabric distribution and bioturbation index of the Silesian Muschelkalk. *1* – evaporites; *2* – dolomites; *3* – limestones; *4* – marls; *5* – cellular limestones; *6* – oncoliths; *7* – sponge-coral bioherms; *8* – stromatolites; *9* – omission surface (hardground); *10* – sandstones; *11* – claystones; *12* – maximum flooding zone; Rh – *Rhizocorallium*

ter. Updated summary on this topic one may find in reviews by Veizer (1994) or Hoefs (1997). However, some virtual problems are worth mentioning for further discussion on the obtained data.

Stable isotopes composition in natural marine waters result as aftermath of manifold environmental controls (see e.g. Hoefs, 1997). Considering the Germanic Basin as a partly closed, peripheral sea of the open ocean and regarding its subtropical paleogeographical position one may assume that the isotope composition of its seawater was basically controlled by interplays between marine vs. continental water influx and by evaporative fractionation factor. Consequently, we can expect that the Muschelkalk seawater was evaporatically enriched in ^{18}O during the periods of restricted circulation (i.e. during the semiclosed phases). An opposite trend, i.e. the ^{18}O depletion was involved by early meteoric diagenesis during the late highstand intervals or by climate pluvialisation and riverine influx. On the other hand the oxygen depletion might have also resulted from deepening and relative cooling of the bottom waters during prominent transgressive intervals.

Unlike the oxygen isotopes, the C-fractionation is less reactive for the evaporation effects, so the variations in $\delta^{13}C$ could be assumed as a net balance of the seawater and meteoric water contribution. For instance, an increase of meteoric water input results in ^{13}C depletion in seawater while the transgressive events should improve the water exchange with oceanic reservoir and hence give more positive, "normal" marine signals within the epicontinental sea.

Since the Muschelkalk transgressive deposits show $\delta^{13}C$ values comparable with the $\delta^{13}C$ contents from the open marine Tethys basins (1‰ to 4‰ PDB) (Masaryk *et al.*, 1993; Frisia-Bruni *et al.*, 1989, own unpubl. data from Northern Calcareous Alps and Inner Carpathians) the above assumption seems to be very appropriate for the Muschelkalk Basin. In conclusion, the below presented discussion on stable isotope records of the Germanic Basin evolution is based essentially on the ^{13}C fluctuations while the $\delta^{18}O$ is considered as an aiding parameter.

^{13}C AND ^{18}O EVOLUTION HISTORY

The most complete series of the stable isotope signals have been obtained for the Upper Silesian succession encompassing interval from the upper Röt to Grenzdolomit, i.e. from late Scythian to early Carnian time (Fig. 25). The other sections (Figs. 26–28) have yielded data on lateral variations in seawater chemistry. The $\delta^{13}C$ curve from the Upper Silesian succession, shows several stages in seawater evolution.

Stage A (Upper Röt–Lower Gogolin Beds)

An increasing influence of marine waters may be interpreted according to $\delta^{13}C$ positive shift from -6‰ to -1‰ vs.PDB. This stage corresponds generally to the initial phase of the Muschelkalk transgression. A slight negative shift at the top of the Lower Gogolin Beds falls in the An 4 sequence boundary (Zellenkalk 2) and reflects the meteoric diagenesis (see chapter on depositional sequences). Almost covariant changes of ^{18}O contents could be explained in the same way.

Stage B (Upper Gogolin Beds–Górażdże Beds)

The transgression of the sequence An 2 is fairly followed by positive trend in $\delta^{13}C$ values. Also the maximum $\delta^{13}C$ value (3.5‰) coincides with maximum flooding event of the sequence and with appearance of the tethyan cephalopods and gondolellid conodonts in Upper Silesia (Assmann, 1944; Zawidzka, 1975). The subsequent negative trend (to -0.5‰) is characteristic for the highstand phase up to emersion (recorded in the Górażdże Beds) and reflects the meteoric and/or mixed water diagenesis.

Reaction of ^{18}O was similar until the highstand phase where the evaporitic enrichment gave shift toward positive values. An opposite trend is visible within the topmost, meteorically-influenced part of the Górażdże Beds.

Stage C (Terebratula Beds–Diplopora Beds)

This stage could be divided into several intervals. The heaviest values both of the $\delta^{13}C$ (3‰) and $\delta^{18}O$ (-3‰) are falling around the maximum flooding interval of the Terebratula Beds.

From the highstand interval onward (Karchowice Beds –Diplopora Beds) the both curves show slight negative correlation, plausibly explained in terms of restricted circulation and evaporation effects. The most negative ^{13}C values at the Diplopora Beds/Tarnowice Beds boundary (the boundary of the sequence An 4), correspond to the most pronounced regression of the Muschelkalk.

Stage D (Tarnowice Beds–Wilkowice Beds)

Most of the carbonates from the Tarnowice Beds are cropping out in eastern Silesia that underwent advanced metasomatosis hence this stage is poorly supported by reliable results of stable isotope signals. Nevertheless a distinctive positive trend of $\delta^{13}C$ to values about 0‰ is consistent with TST of the sequence La 1. The stage D was a turning point in isotope chemistry of the Upper Silesian subbasin since unlike the precedent stages, this one exhibits a drastically opposite course of the $\delta^{13}C$ and $\delta^{18}O$ curves. Such a trend dominated up to the end of the studied succession, i.e. up to the early Carnian.

Stage E (Boruszowice Beds–Lettenkeuper (Sulechów Beds)–Grenzdolomit)

The above discussed dramatical environmental changes in Longobardian time (pluvialistation and land denudation) are reflected in substantial depletion in $\delta^{13}C$ values (< -5‰) recorded in the lower Keuper deposits. An intense influx of isotopically light fluvial waters involved a negative shift visible already in marine Boruszowice Beds (corresponding to the maximum flooding event of the Ladinian) and in brackish Lettenkeuper carbonates.

The ^{13}C depletion increases outside the gate domains and reaches -8‰ toward the northern margin of the basin (Ośno profile) as early as in late Fassanian time (see Fig. 28).

The strong positive excursion of the ^{18}O is contradictory with the general environmental changes since the concurrent emersion and pluvialisation phenomena should cause obvious ^{18}O depletion. This contradiction could be plausibly interpreted as an aftermath of the onset of concomitant spreading and volcanism overwhelming the tethayn rifts. Volcanic outpourings and hydrotherms supplied to the ocean light carbon and heavy oxygen isotopes (Muehlenbachs, 1986) and hence "produced" isotopically different seawater. This inference is supported by highly radiogenic $^{87}Sr/^{86}Sr$ found in the upper Muschelkalk carbonates of the German Basin (Korte *et al.*, 1998). This phenomenon would be also in agreement with other manifestations of coeval endogenic processes, e.g. hydrothermal oremineralisation which was common in the entire Tethys area (see e.g. Bogacz *et al.*, 1975; Bechstädt & Dohler-Hirner, 1983; Macquar, 1984). Similar negative isotopic correlation found by me in the Ladinian Reiflinger Beds (within interval with the *pietra verde* intercalations) of the Karwendel Group in the Northern Calcareous Alps (profile Engalm,

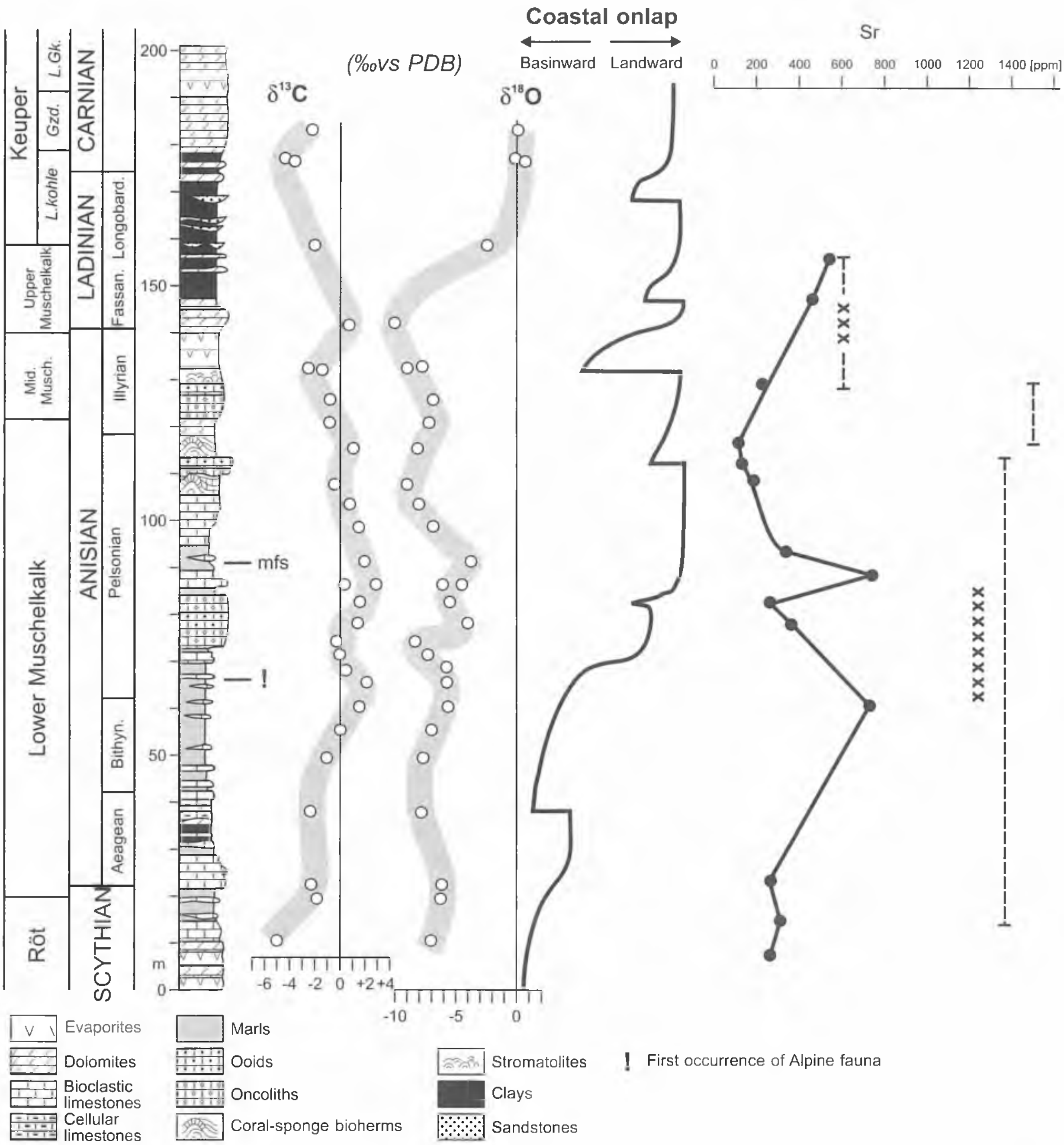

Fig. 25. ^{13}C and ^{18}O isotope and Sr- index curves of the late Scythian–Carnian marine succession in the Silesian Basin plotted against the coastal onlap curve. The Sr mean contents from Thuringia (xxxx) and from SW Germany (— —) also presented for comparison

preliminary data, study in progress) confirms the inference.

LATERAL VARIATION IN THE STABLE ISOTOPE CONTENTS AND PALEODEPTH ESTIMATION

As indicated by the δ^{13}C curves from various sites of the Polish Basin, the isotope composition show generally similar overall course (see Fig. 29). Some subordinate differences, e.g. the negative excursion in the upper Muschelkalk of northwestern Poland could reflect fingerprints of local environmental factors.

The conclusion about the better communication of the East Carpathian Gate with the Tethys by the end of Fassanian time, inferred earlier from paleontological data (cf. the chapter on La 1 depositional sequence) is reflected also in the ^{13}C signals which are more positive in the Holy Cross Mts. than in Upper Silesia.

On the other hand the Holy Cross Mts area was situated within the NE margin of the Muschelkalk Basin. Therefore, the ^{13}C from the lower portion of the Muschelkalk succession in the Holy Cross Mts. displays generally more negative values as those from the other parts of the Polish Basin. This phenomenon could be ascribed to a significant freshwater influx from the nearby land. The "mixing" setting of the Holy Cross Mts. section is visible also in the δ^{18}O curve

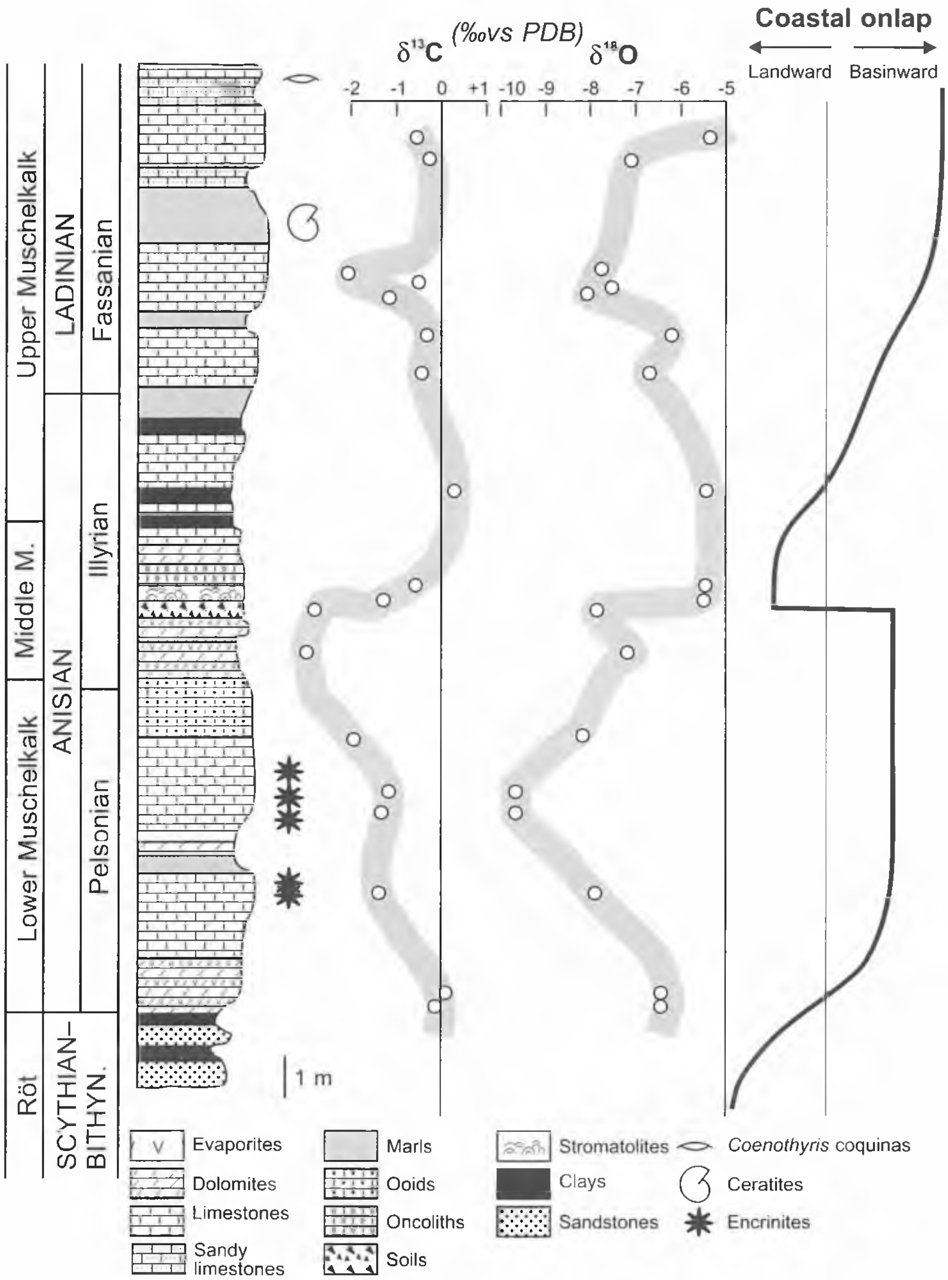

Fig. 26. $\delta^{13}C$ and $\delta^{18}O$ curves of the Anisian–Ladinian marine succession in the northern Holy Cross Mts. plotted against the coastal onlap curve

that varied in wide range (from -5 to -10‰, Fig. 26). The fluctuations of the stable isotopes contents from the inner parts of the basin (Lower Silesia and Polish Lowland) show a more gradual evolutionary trend. This concerns in particular the ^{18}O signals ranging between -6‰ and -7‰ (Figs. 27 and 28). Such a smooth isotopic course suggests a stabilised chemistry and temperature of the seawater as well as an equlibrium fractionation of carbonate precipitates.

An attempt of oxygen isotopes application in paleobathymetry reconstruction has been carried out according to method by Adlis *et al.*, (1988). The paleodepth estimation has been applied for the maximum flooding phase of the Terebratula Beds in Upper Silesia. First, I have assumed that during this extremely rapid transgressive event, the oxygen isotopic signal from the starved basin was controlled essentially by water cooling following the increasing water depth. Three specimens of the brachiopod *Coenothyris vulgaris* have been chosen for temperature/depth estimation procedure. The first one (B1) comes from the so called Hauptcrinoidenbank formed obviously within the storm wave base (no deeper than 15–20 meters) (Fig. 11F). The second specimen (B2) was collected some 1.5 m above the first one and the last one (B3) from the 4.5m-higher situated horizon representing the maximum flooding surface (Fig. 11 G). The obtained ^{18}O gradients ($\Delta\delta^{18}O$) were respectively; 1.8 ‰ (between B1 and B2) and 1.2‰ (between B2 and B3).

The translated temperature differences would be ca.

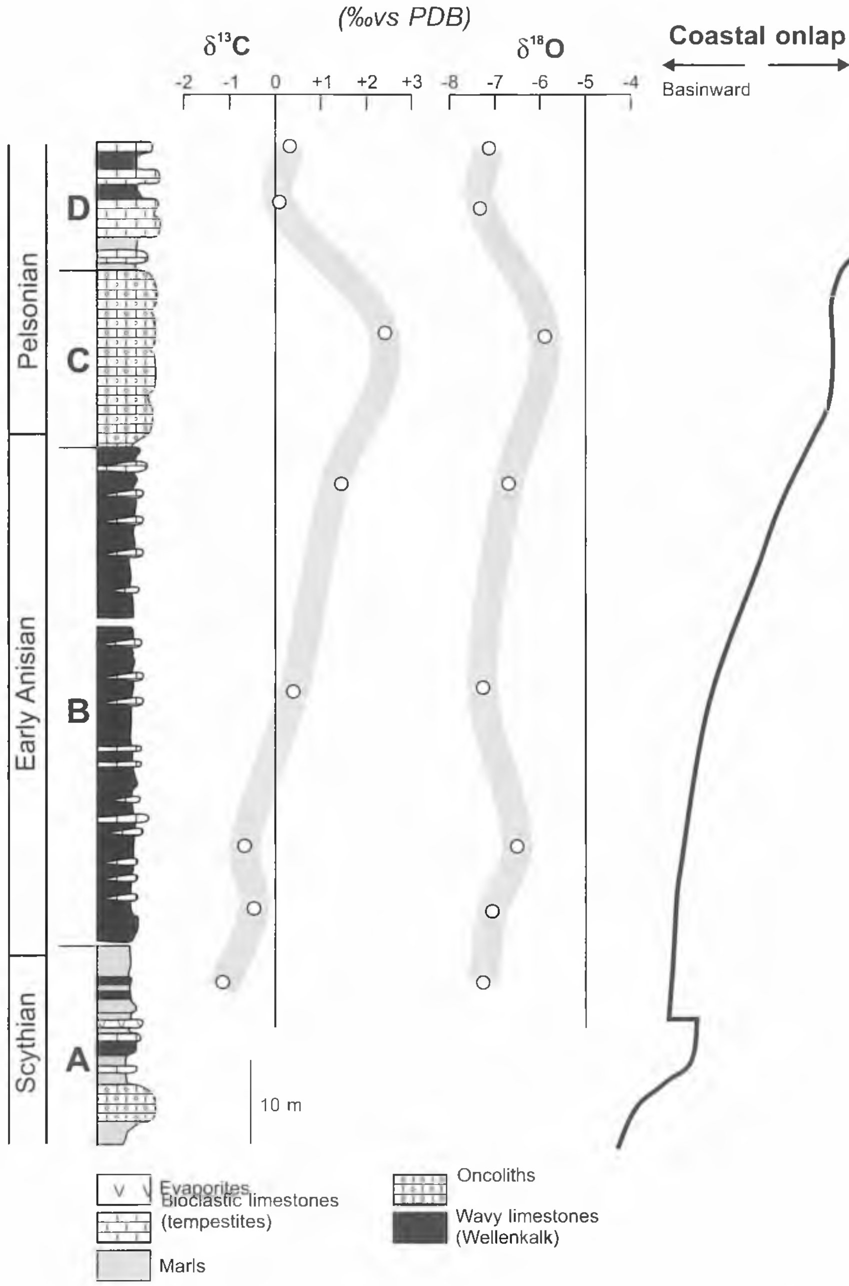

Fig. 27. $\delta^{13}C$ and $\delta^{18}O$ curves of the late Scythian–Anisian marine succession in Lower Silesia plotted against the coastal onlap curve. A–D: tentative lithological units by Szulc (1991) that correspond approximately to the following Upper Silesian units: A – Lower Gogolin Beds, B – Upper Gogolin Beds, C – Górażdże Beds, D – Terebratula Beds. Early Anisian/Pelsonian boundary after Kędzierski (1996)

9°C and 6°C, respectively, for the above isotopic gradients. Referring the temperature gradients to the bathymetry (with regards to the starting point of 20 meters in depth), we get the paleodepth of the Upper Silesian subbasin reaching 110–150 meters during the maximum transgressive stage. Such a depth is not in contradiction to the above discussed sedimentological and paleobiological indicators.

Sr CONTENT WITHIN THE MUSCHELKALK CARBONATES

The Sr distribution along with celestite mineralisation could be used to decipher the paleocirculation pattern and water chemistry within the Muschelkalk Sea. The obtained Sr content in the Upper Silesian Muschelkalk matches very well the $\delta^{13}C$ fluctuation (Fig. 25).

The highest values (700–800 ppm) correspond to the maximum transgression events of the Upper Gogolin and Terebratula Beds. The lowest concentrations (around 100–150 ppm) are featuring the reefal limestones of the Karchowice Beds and oolitic Diplopora Beds. Also the strontium sulphate (celestite) crystals occur very sporadically (and exclusively) within the maximum flooding intervals. The strontium was probably derived from calcitised aragonitic bioclasts.

The Sr concentration and celestite scarcity from Upper

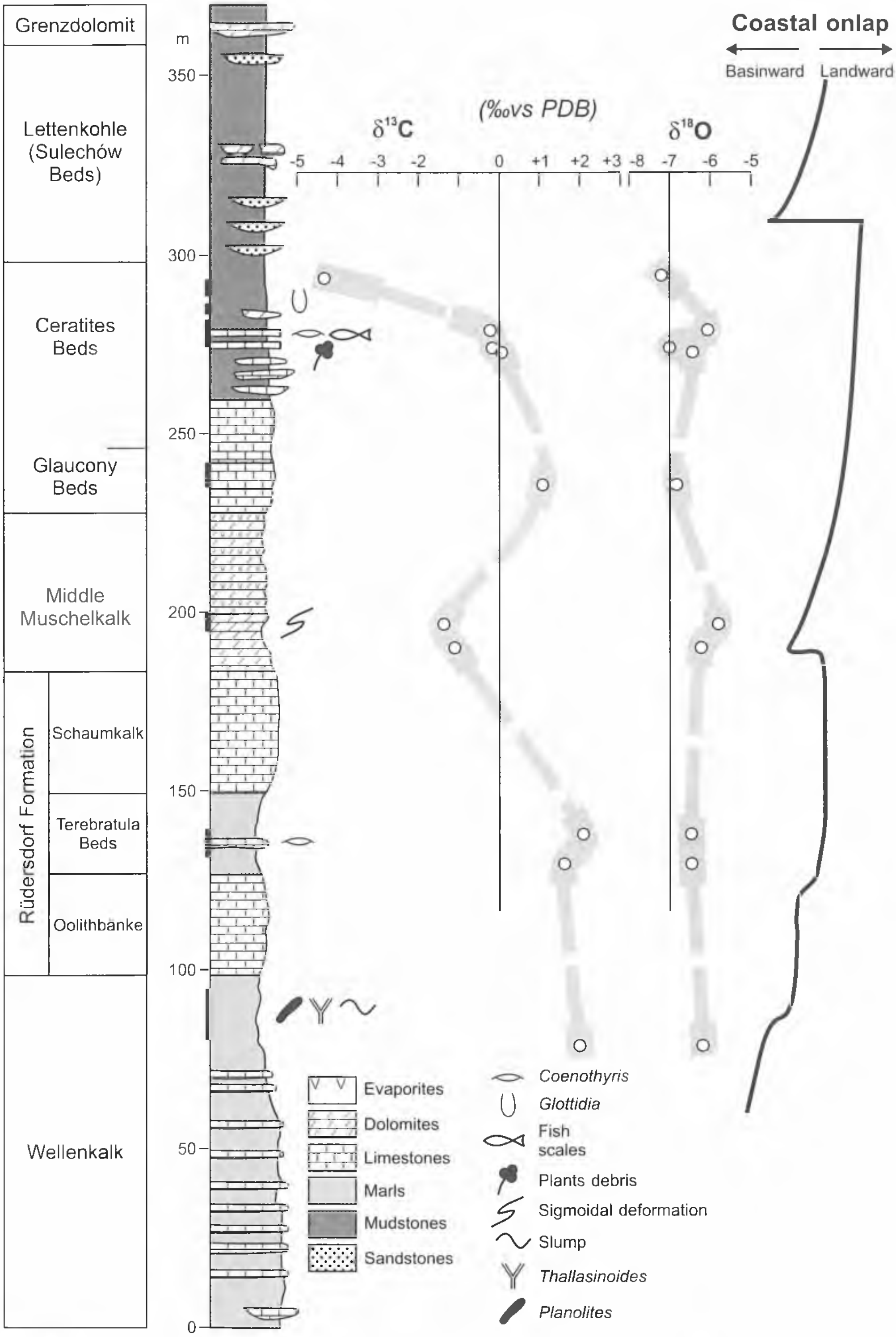

Fig. 28. $\delta^{13}C$ and $\delta^{18}O$ curves of the Anisian–Ladinian marine succession in western Poland (Ośno borehole) plotted against the coastal onlap curve

Silesia contrast drastically with the Sr content from the lower Muschelkalk of Thuringia and SW Germany where it ranges between 500–2000 ppm and averages 1100 and 1300 ppm, respectively (Fig. 25; Riech, 1978; Langbein & Stepansky, 1996). Intensive celestite mineralistion is visible already in the western Poland (cf. Fig. 6). Higher concentrations of Sr and ubiquitous celestite mineralisation within the lower Muschelkalk carbonates of SW Germany, evidence an evaporitic enrichment of the marine waters with strontium salts under restricted exchange with the open ocean (Riech, 1978).

The oxygen stable isotope signals confirm also evaporitic depletion of the surface water in ^{18}O in the central Muschelkalk Sea (Korte *et al.*, 1998). All these data are in

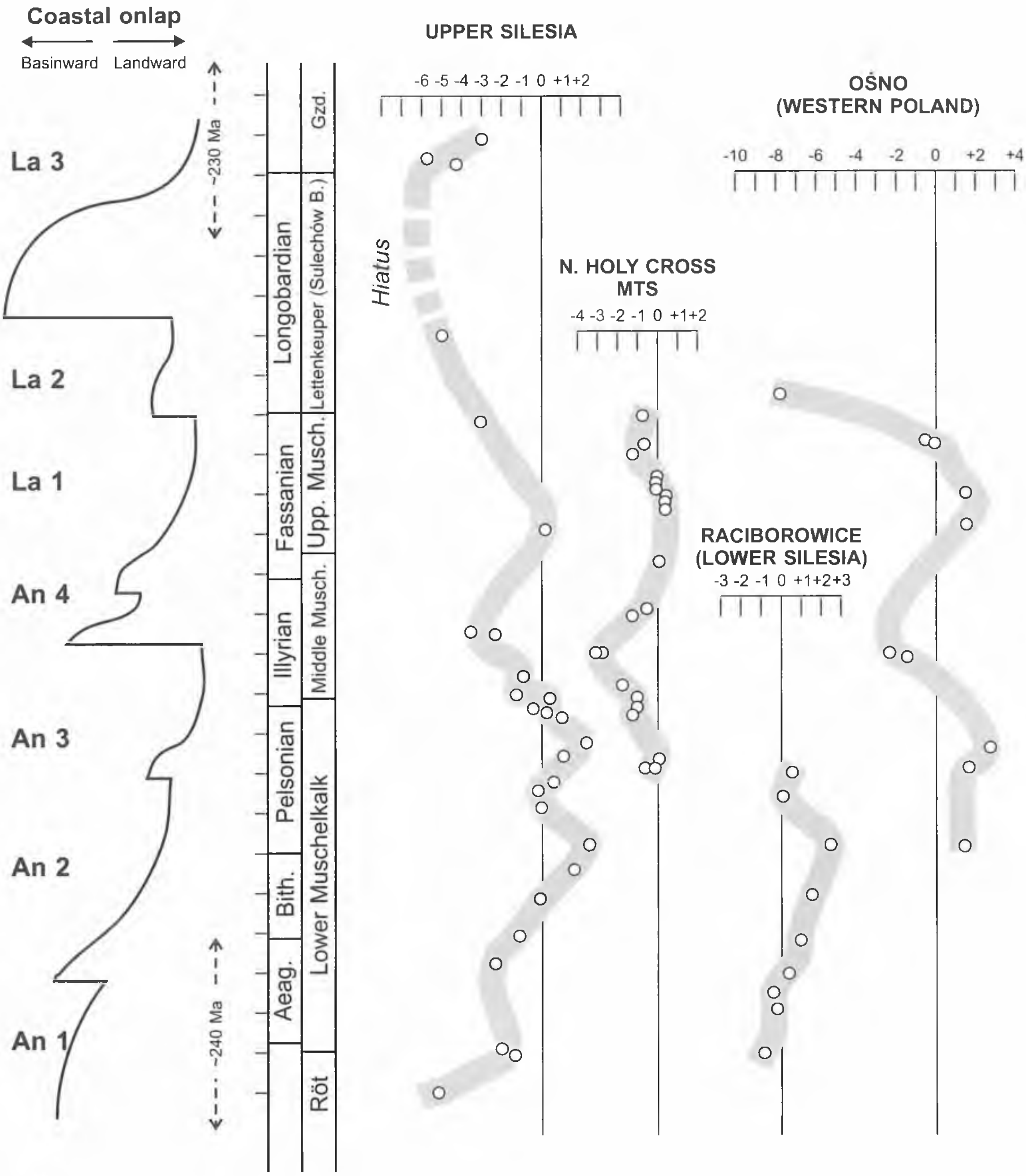

Fig. 29. $\delta^{13}C$ curves of the late Scythian–Carnian successions in the Polish Basin plotted against the sequence depositional framework. Modified from Szulc (1999). The time scale is adapted from Gradstein *et al.*, (1994) however with except for the absolute ages of the beginning and end of the studied interval. The ages seem to be very vague in a light of the recent radiometric studies (Mundil *et al.*, 1996; Brack *et al.*, 1999)

agreement with the above proposed model of semi-closed basin maintained by influx of fresh oceanic water *via* the eastern gates. Moreover, the evaporation effect was likely reinforced by different paleolatitudinal position of the western and eastern parts of the Germanic Basin. As shown at Fig. 1, the latitude gradient between the NE and SW parts of the basin reached as much as 10° what might have given the mean annual temperature of some 5–8°C higher in SW Germany compared to the Silesia.

Uniform distribution of Sr concentration in the upper Muschelkalk (ranging in Silesia, Thuringia and SW Germany between 450–800 ppm) and lack of celestite mineralisation signify that all the gates were opened and free, open circulation dominated in the basin.

CLIMATE EVOLUTION IN THE TETHYS DOMAIN DURING LATE SCYTHIAN–CARNIAN TIMES AND ITS CONTROLS

In all of the sofar constructed models of the Triassic paleogeography, the area under discussion is located always within the subtropical belt, i.e. between 20° and 35° of the northern paleolatitude. Such a position determined semiarid to arid climatic conditions as indicated also by lithofacies criteria (redbed deposits) and paleontological (including palynological) data (Van der Zwan & Spaak, 1992).

The trade winds were the dominant airmass circulation system (see Fig. 1) and they involved low rainfall amount over the NW Tethys and Peri-Tethys Basin. The ocean-continent configuration might have favoured the monsoonal circulation in some parts of the basin (Parrish *et al.*, 1989; Van der Zwan & Spaak, 1992) but the late Scythian–Carnian Peri-Tethys is not this case. Instead the monsoon influence, the region suffered heavy subtropical storm activity (Aigner, 1985).

The sedimentological and geochemical criteria indicate, that the late Scythian–Anisian interval was generally controlled by semidry to dry climate with a very pronounced evaporation. The climate changed since Fassanian onward and the upper Muschelkalk and lower Keuper deposits formed under relatively humid and warm climate. According to paleobotanical data a rich plant community conquested the land area (Grodzicka-Szymanko & Orłowska-Zwolińska, 1972).

Palynofacies composition of the upper Muschelkalk deposits in Silesia (Boruszowice Beds) is dominated by lycopodiophytes (*Aratrisporites* sp.), i.e. mangrove vegetation characteristic for humid conditions (A. Götz, pers. comm.). This in turn implies a high rainfall amount favouring plant expansion. Since the paleolatitudinal position of the basin did not differ significantly from this of Anisian–early Ladinian times, another causes of the climate pluvialisation should be considered.

The intensive fluvial activity and the resulted incised valley system suggest tectonically-controlled topographical rejuvenation. On the other hand the pluvialisiation phenomenon coincides with particularly intensive volcanism registered in all the Alpine basins (see e.g. Gwinner, 1978), Apennines (Martini *et al.*, 1986), Carpathians (Cros & Szabo, 1984), Iberia (Marfil *et al.*, 1998) and the eastern Tethys domain (Sengör *et al.*, 1993).

Referring the dramatical climatic effects of modern, local volcanic eruptions (Thorarinsson & Vonnegut, 1964; Bourne, 1964) onto the discussed overregional Ladinian volcanism, a substantial increase of runoffs and cyclonic circulation should be expected in the western Tethys Basin. A prominent increase of the vapour condensation nuclei in the troposphere and subtropical cyclone activity, could led to intensive rainfalls in the entire western Tethys domain.

Furthermore, a substantial cooling of Earth surface could be expected as ensuing effect of the increasing cloudiness (Polack *et al.*, 1976). The last inference is contradictory to a generally assumed conjectural model of a greenhouse state resulted from the late Triassic volcanism (Veevers, 1989; Simms & Ruffel, 1990). As a matter of fact, Sigurdsson (1990) has evidenced that contribution of the volcanogenic CO_2 to its atmospheric reservoir is negligible (even for the most conspicuous volcanic events) hence the concept of the late Triassic greenhouse warming of the western Tethys is inappropriate.

The volcanic "factory" was situated to south of the Germanic Basin. Since the northern Peri-Tethys area was dominated by the northeastern trade winds (i.e. blowing against the volcanic area) (see Fig. 1), no direct evidences of volcaniclastic fallouts has been found sofar in the Germanic domain. However, it must be stressed that the silicate components (volcanic ash) are subordinate in the volcanic aerosol and they could influence climate changes only within a few hundred km from the eruption center (Carey & Sigurdsson, 1982). In fact the sulphuric acid aerosol is the main volcanic volatiles capable to form the condensation nuclei (Sigurdsson, 1990). The sulphuric acids carried much higher as the volcanic ash might have been transported by the "westerlies", i.e. the upper tropospheric/stratospheric winds moving in opposite directions to the underlying trade winds (Chromow, 1973). Hence the upper winds brought over the Peri-Tethys a huge volume of condensation nuclei which gave rise to increase of rainfall amount and climate pluvialisation.

In conclusion, the volcanic activity during Ladinian–Carnian times forced the climate pluvialisation and resulted in a substantial decrease of the mean annual temperature over the whole western Tethys domain. This phenomenon is convincingly demonstrated by coeval appearance of sedimentary facies typical for humid environments. The Germanic Lettenkeuper "wet" facies have their equivalents in the Southern Alps (Livinallongo Formation, Buchenstein Formation, Wengen Group), in the Northern Calcareous Alps (Reifling and Partnach Formations) (Rüffer, 1995; Rüffer & Zühlke, 1995) and in the Carpathians; Nemesvamos Mb. in Balaton area (Budai & Haas, 1997); Kozar-Kantavar Beds of the Mecsek Mts. (Török, 1997) and in many others tethyan basins. Irrespective of the depositional setting, all the mentioned facies display a high bituminous content, lack of evaporites and common association of igneous rocks.

It is very likely that the volcanic activity and topographic rejuvenation have been causally associated with vigorous spreading and tectonic reconstruction within the Tethys rifting belt (Bechstädt *et al.*, 1976; Füchtbauer & Richter, 1983; Brandner, 1984; Megard-Galli & Faure, 1988; Baud *et al.*, 1991).

TECTONIC CONTROLS

As shown above, despite of the rift-peripheral position, the Germanic Basin was affected by syndepositional tectonism during Triassic times. Evidences of synsedimentary tectonics are known from the lower and middle Buntsandstein over the entire Peri-Tethys area. Most of the structures are tensional grabens and dilatation cracks developed within the Triassic deposits (Schüller *et al.*, 1989) or affected also the older basement rocks. The latter deformations occur in the eastern Upper Silesia (pers. observations) but they are particularly well developed in the Holy Cross Mts. where deep (several tens (hundreds?) meters) clastic dykes filled with the Buntsandstein sands penetrate the Paleozoic rocks (Głazek & Roniewicz, 1976).

A particular basinwide tectonic activity featured the middle Bundsandstein interval when intensive block fault-ing resulted in regional unconformity called the Hardegsen Diskordanz. This unconformity is correlatable from the Netherlands and northern Germany to central Poland (Geluk *et al.*, in prep.). It must be stressed however, that but the Hardegsen tensional phase, the overwhelming part (the central and northern in particular) of the Germanic Basin was controlled by thermal subsidence dominating also in Middle Triassic time (Geluk, 1998).

An intensive syndepositional tectonism has been also inferred for the Muschelkalk carbonates. Szulc (1990, 1993) has first recognised and employed the tectonicall-yinduced deformational and sedimentary structures and sequences to reconstruct the crustal dynamics within the Silesian Muschelkalk. Afterward, similar fabrics have been reported from the Thuringian Muschelkalk (Voigt & Linnemann, 1996; Rüffer, 1996) and Brandenburg (Dualeh, 1995). Some deformational structures found in Baden-Württemberg (Schwarz, 1970) and Holy Cross Mts (Bialik *et al.*, 1972) have been also earlier supposed to be quake-generated phenomena.

Taking into account the distribution of the tectonically-controlled sedimentary and deformational structures it appears evident that most of them are grouped in belts linked the ancestral, Hercynian mostly, faults and lineaments. This agrees with a general model of rift-forming processes of Vauchez *et al.*, (1997) which suggests a preferential superposition of new rifting upon older discontinuities. The most important structures in the Germanic Basin were the Teisseyre-Tornquist Zone (TTL), Cracow (Odra)–Hamburg Fault Belt (COHF), Elbe Fault (EF), Silesian-Moravian Fault (SMF), the Saxothuringian Lineament (STL) and the Cevennes–Villefranche Fault belt (CVF) (see Fig. 2). During Middle Triassic time these inherited structures were reactivated and they influenced sedimentary processes and tectonic subsidence within the pertained regions. No such intensive crustal mobility has been registered outside these regions, what indicates a decrease in tectonic activity and a growing control of thermal subsidence within the central and northern parts of the Germanic area.

As demonstrated above (Fig. 14) the depocenters of the Germanic Basin moved with time. Four main phases of structural evolution could be distinguished in the discussed part of Triassic. During the first phase (Röt–lower Muschelkalk) the subsidence center followed the system; SMF – COHF – STL. The second phase (middle Muschelkalk) was a turning stage, because the depocenter started to move to the western system encompassing the southern STL and the CVF. This subsidence center was dominating during the third phase of basin evolution (upper Muschelkalk–lower Keuper).

The phases differ in their tectonic regime. The first phase (late Scythian–mid Anisian) displayed tensional tectonics developed along the southern margin of the basin from the Holy Cross Mts. through Upper and Lower Silesia to Thuringia. Considering the inherited structural framework featured by oblique dislocations (Żaba, 1996) and the obliquely migrated depocenter(s) of the Polish Triassic basin (Dadlez, 1989; Hakenberg & Świdrowska, 1998) the strike slip movement seems to be the dominate crustal motion during the first tectonic phase. After very thorough study on a fault network developed within the Carboniferous and Triassic rocks of the Upper Silesian Coal Basin, Herbich (1981) has found out that the Muschelkalk deposits underwent synsedimentary strike slip motion and the displacements reproduced essentially the precedent Hercynian strike slip dislocations. Jowett (1986) has ascribed the Pb-Zn mineralisation in Upper Silesia to the onset of the tensional crustal thinning and the ensuing upward migration of ore-bearing fluids proceeded in Middle Triassic.

The second phase (late Pelsonian–Illyrian) was featured by the lessen crustal mobility while the third phase (Ladinian) displayed a moderate tensional regime in the western system and vigorous compression (transpression) in the eastern area. The compression encompassed finally (Muschelkalk/Keuper boundary) also the western basin and resulted in regional angular unconformity (Wohlburg, 1969) traceable over the whole German Basin.

The last phase (late Ladinian–early Carnian) in the studied interval of the basin history commenced with a relatively lessened tectonism as suggested by a very uniform facies development over the entire peneplanized basin, especially well expressed for the Grenzdolomit transgressive deposits (see Figs. 12E, 16). Forceful crustal movements began again in Carnian time (lower Gipskeueper) when an intensive rifting involved the North Sea basin and NW Germany (Frisch & Kockel, 1998). No such remarkable tectonism affected the southern and eastern parts of the basin, which were mainly controlled by thermal subsidence. It seems that in this time, the northern parts of the basin were rather influenced by Proto-Atlantic rifting than by the Tethys spreading.

Only during the Schilfsandstein deposition the rifting encompassed the whole basin and brought a conspicuous upwarping of the northern Peri-Tethys area. Given the concurrent up and down block movements within the basin one may assume the translatory motion as dominant tectonic mechanism for this time. The translation is especially well documented by the flower-like pattern of the Upper Triassic faults of the Foresudetic area (Deczkowski & Gajewska, 1977). The Schilfsandstein fluvial anastomosing channels were obviously superimposed upon the graben network (Dittrich, 1989) while the uplifted blocks were eroded and gave way to a prominent regional unconformity.

The outlined tectonic history of the Germanic Basin corresponds well with the structural evolution of the intra-Tethys belt. The late Scythian–Pelsonian transtensional tectonics, expressed mostly in the Germanic Basin in form of stacked seismic events may be correlated with complex block movements controlled by the transform motion (Montenegro Phase of Brandner, 1984) and registered in southern alpine domains and on the Tisia Plate (Bechstädt *et al.*, 1978; Brandner, 1984; Senowbaryi-Daryan *et al.*, 1993; Szulc, 1993; Konrad, 1998). Also the second, tectonically "quiet" phase during Illyrian time had its counterparts in the southern alpine basins (Bechstädt *et al.*, 1976; Martini *et al.*, 1986). It is noteworthy that no such coincidence with the 1st and 2nd phases have been observed for the Northern Calcareous Alps and the Carpathian Middle Triassic successions.

The third, Ladinian–Carnian phase featured by transpressive regime in the the northern Peri-Tethys was accompanied by a very intense transtension, crustal thinning and volcanism which affected the Neo-Tethys area (Bechstädt *et al.*, 1976; Martini *et al.*,1986; Megard-Galli & Faure, 1988; Krainer & Lutz, 1995). Brandner (1984) named this interval as Labinian tectonic phase and referred it to a substantial intensification of sea-floor spreading within the Tethys belt. At the same time, to the east, the Paleo-Tethys Ocean (cf. Fig. 1) became closed as the Cimmeria block started to collide with Europe (Sengör, 1984).

From the above presented notions becomes clear a very intimate tectonic fate of the Tethys and its northern periphery. Therefore, it is reasonable to assume that the same drive mechanism controlled the structural evolution of the both basins. The complex spreading of the Tethys Ocean seems to be the principal control of the structural reorganisation of the western Tethys domain. As a rule the rejuvenated Hercynian faults appeared to be the main transmission ways of the tectonic strain both inside the Tethys area (Brandner, 1984; Yilmaz *et al.*, 1996) and at its periphery (Szulc, 1993). The tectonic motion born in the Tethysside had been transmitted to the northern Peri-Tethys along inherited Hercynian dislocations.

The "tethyan" controls seem to dominate in the eastern basin, what suggests a close (direct?) structural link between the eastern basin and the tethyan rift belt. According to faunal documentation, the eastern Germanic Basin (the Silesian, above all) shows more similarities to the Southern Alps paleocommunities than to the other Alpine basins. It implies in turn, conclusions about a close paleoposition of these two basins in Middle Triassic times. A similar tectonic history of the Upper Silesian and south Alpine basins corroborate the paleontological data. Therefore it seems very likely that the Silesian-Moravian Gate and the southern Alpine basin were influenced by the same master fault system (Fig. 1).

The connections between the western Germanic Basin and the Tethys were substantially modified by intermediate blocks of the South East Basin (S. France), Prealps and western Alps (Baud & Megard-Galli, 1975; Debelmas, 1986). As already noted the northern and NW parts of basin were controlled by the North Atlantic-Arctic rifting belt.

The most striking feature of the Peri-Tethys evolution is the diachronous sedimentary succession, depending on the earlier transgression and earlier, final regression in the eastern part of the Peri-Tethys. This, in turn, resulted from the diachronous opening and closing of the seaways. The eastern gates were opened already in the late Induan–early Anisian, while the western gate was opened not before the Pelsonian. The westward relocation of communication pathways could be explained by the ocean spreading, which shifted from the east to the west (Szulc, 1997a). The relocating openings and closings of the seaways (Paleo-Tethys and Neo-Tethys trenches, cf. also Fig.1) can be plausibly explained by using the model by Doglioni (1992) assuming an oblique and rotational motion governing the Tethys spreading which resulted in splitting of the terranes and their gradual eastward drifting up to a collision stage.

Halokinesis

The fault tectonics within the Germanic Basin involved remobilisation of the underlying Zechstein salts as early as in Induan time (Geluk, 1998; Strunck *et al.*, 1998). The halokinesis continued also in Middle Triassic time and resulted in development of small subsidence centers with sediment infill, 2 – 3 times thicker as in the neighbouring, inaffected areas (Fig. 14, Gajewska, 1977)

Particularly vigorous salt tectonics took place in Carnian time when the transpressive motion forced the emplacement of salt diapirs in the whole Germanic Basin (Frisch & Kockel, 1998). A some feedback reaction favoured salt tectonics; the transpression forced remobilisation of the salt on the one hand, while the salt served as easy-slip matter for fault displacements on the other hand. The halokinetic movements comprised also the Triassic evaporites. Recently I have observed in Upper Silesia, along the A4 highway (under construction) an intensive diapirism of the Röt gypsum deposits. Since the diapirs do not disturb the overlying dolomites and limestones the tectonic trigger (but not the charge mobilisation) of the salt flowage is evident.

SEAWAYS AND THEIR CONTROLS – A NEW INSIGHT

As mentioned already, the communication between the Tethys and Germanic Basin was maintained by several depressions cutting across the elevated Vindelico-Bohemian Massif. Based on paleontological data, Senkowiczowa (1962) postulated that the fauna migrated from the Tethys to Germanic Basin through three seaways; the Burgundy Gate to the west and the East Carpathian and Silesian Gates to the east. This model has been generally accepted and reproduced in many paleogeographical reconstructions (e.g. Ziegler, 1990). Analysis of new data, in particular the sedimentological criteria and the ensuing analysis of basin evolution supported by better biostratigraphical dating provide a good foundation for reinterpretation of the mechanisms controlling connections between the Tethys and its northern periphery.

As suggested by the facies arrangement interpreted from the present distribution of the deposits within the Upper Silesia area, the Silesian-Moravian seaway was certainly much wider as it was proposed in the hitherto done reconstructions. It concerns in particular the Anisian maximum flooding intervals represented at present only by offshore carbonate facies. Regarding the lack of preserved marginal facies deposits and considering the very probable flat morphology of the peneplanized Vindelico-Bohemian Massif one may assume that during Anisian time, the transgression overlapped far upon the western margin of the Silesian-Moravian Gate and reached the inner parts of the Massif (see Fig. 12B). It seems also likely that the Małopolska Massif that divided the Silesian-Moravian Gate from the East Carpathian Gate was rather a narrow (some 100 km) complex of horsts and grabens than a compact and large land block. Nevertheless this high-relief klippen range hindered a free communication between the East Carpathian

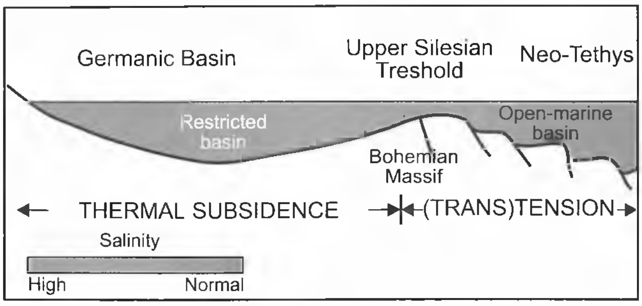

Fig. 30. Schematic model of the basin dynamics and circulation regime within the Northern Peri-Tethys domain

route with the Silesian province as evidenced by their faunistic and facies diversities.

The lithofacies differences resulted from the contrasted tectonic regime controlling the both depressions. As suggested by the facies arrangement and isopach pattern (Figs. 12B, 14) the East Carpathian Gate was gently inclined homoclinal depression while the topography of the Silesian-Moravian Gate was much more complex.

The southern Polish depression(s) developed already in early Triassic times (see Fig. 3) and was separated from the northern and western parts of the Germanic Basin. The isopach pattern is apparently at variance with sedimentary facies developments. For instance, the fully marine carbonates of the Röt and lower Muschelkalk from Upper Silesia are significantly thinner as the evaporites deposited northward in the restricted basin center (cf. e.g. Fig. 7 and Fig. 12A). This phenomenon can be plausibly explained only in terms of diversified subsidence rate and contrasting circulation regime. The Silesian-Moravian Gate was presumably a less subsiding treshold block strongly influenced by a normal marine influx from the Tethysside while the thermally subsiding external parts subjected restricted conditions under semiarid climate. It means that the Upper Silesian subbasin should be regarded rather as a segment of the northern margin of the Tethys Ocean than an intrinsic part of the Germanic Basin (Fig. 30). Such an inference is confirmed by the tethyan fauna distribution which often does not exceed the Upper Silesian region. The location of the Pelsonian reef buildups is the best evidence for this interpretation. Considering the ecologically determined position of the reef buildups at the carbonate platform or ramp setting, the Silesian sponge-coral reef belt should be treated as a Tethys marginal reefal rim dividing the offshore, tethyan open marine zone from the backreef area encompassing almost the entire Germanic Basin situated to the north and northwest of Silesia. As suggested by the correlation of depositional sequences, the Upper Silesian subbasin pertained to the Tethys domain until late Anisian time.

In contrast to the relatively well defined position of the eastern gates the unequivocal determination of the western gate still remains a difficult problem to solve. The Burgundy area as commonly assumed communication route could not in fact, maintain a free circulation since the western peritethyan area and its neighbouring Alpine basins, were dominated by clastic and/or restricted evaporitic sedimentation (Ricou, 1963; Megard-Galli & Baud, 1977; Courel (coord.), 1984; Courel *et al.*, 1992; Dromart *et al.*, 1992; Carrillat *et al.*, 1999; Courel *et al*, in print). Brunet (1986) postulated even the Burgundy area as a post-Hercynian uplifted block. Furthermore the geographic distribution of the tethyan faunal elements of the upper Muschelkalk in SW Germany (Hagdorn & Simon, 1993) indicates that they did not trespass the Basel latitude (Swiss Jura) to the south (see e.g. Fig. 12D). This all suggests that the SW-German and the southeastern France basins were separated in Middle Triassic time and the possible Tethys–Peri-Tethys link(s) during Ladinian time was located to the east from the Burgundy. It seems that, as already presumed by Einsele and Schönenberg (1964), the Alpenrhein Depression could be one of the candidates for the probable communication pathway with the open marine Tethys basins. It is also very likely that the communication between the German Basin and the Tethys proceeded by more a complex system of depressions.

In conclusion it should be stressed that the use of the term "Burgundy Gate" is not relevant for the discussed gateway. For awhile a term "Western Gate " seems to be more appropriate. Instead the gateway function, the Burgundy area played rather a role of local subsidence center controlled by reactivated Cevennes-Villefranche fault belt as late as in Ladinian time.

CONCLUSIONS

The presented study was focused on the Middle Triassic evolution of the northern Peri-Tethys (or Germanic) Basin, analysed in terms of principal eustatic, tectonic and climatic changes which affected the Western Tethys domain during late Scythian–Carnian time. The gathered data lead to following conclusions.

1. The Germanic Basin was a marginal sea of the Tethys Ocean rather than a typical epicontinental sea. The basin was open to the south (i.e. toward the ocean) and closed from the north.

2. Such a semiclosed setting resulted in a distinctive environmental diversification throughout the basin. The open marine environments occurred only in the Tethys-nearby, southern parts of the basin while northward, the environments became more and more restricted. The restricted circulation along with a hot and dry climate involved substantial deterioration in oxygen availability, increase in water salinity and decrease in energy level. This is clearly reflected in faunal diversity, facies variety and geochemical properties of the sediments.

3. As became obvious from the present study, the thick, halite-bearing evaporitic sequences were formed within the deepest parts (depocenters) of the basin. This inference denies the hitherto accepted shallow water (sabkha, playa) origin of the Röt–Muschelkalk halite deposits.

4. Normal marine conditions prevailed in three regions directly communicated with the Tethys Ocean in different times. The easternmost one called the East Carpathian Gate domain was influenced by the Tethys as early as in Induan time (middle Buntsandstein). The Silesian-Moravian Gate displayed open marine conditions from late Scythian to

early Fassanian time. The Western Gate (called earlier "Burgundy Gate") was open from Pelsonian to early Longobardian time.

5. The present study denies the existence of the "Burgundy Gate" which was sofar assumed to be the western communication pathway linking the Tethys and the northwestern Peri-Tethys. The revision of the paleontological and sedimentological criteria proves that there was no connection between the Germanic Basin and the Burgundy area. I suggests that the likely connection was situated rather NE from the Burgundy (i.e. along the Alpenrhein Depression).

6. The Eastern Carpathian and Silesian-Moravian Gates were closely situated one to the other, but their free communication was hindered by fault-bounded blocks of the Małopolska Massif separating the both gates.

7. According to paleoecological and geochemical data, in late Scythian–Anisian time the Upper Silesian area was intimately related to the Tethys Ocean and in fact represents the ocean margin *s.s.* as indicated, for instance, by the development of the coral-sponge reefs.

8. The above mentioned diachronism of the gate opening, reflects a relocation of the connection pathways following the westward shift of the Tethys spreading center during Triassic times. This mechanism explains also the earlier uplift and disconnection of the eastern part of the Germanic Basin that resulted from closing of the oldest, easternmost branches of the Tethys rifts (Paleo-Tethys).

9. The tectonic motion born within the spreading center was translated onto the rift periphery by a system of reactivated older faults. These faults gave rise to the crustal downwarp and the gates opening.

10. The southern parts of the Germanic Basin (Silesia, the Holy Cross Mts, SW Germany) have been influenced by the Tethys rifts whereas the Northern Germany and the North Sea basins were controlled by the North Atlantic-Arctic rift system. The other, major part of the basin was dominated by thermal subsidence (Fig. 30).

11. Faunal migration from the Tethys into its northern periphery followed generally the rift-controlled opening of the main seaways within the Tethys (see Fig.1). The first tethyan faunal elements, which appeared in the southeastern Polish Basin as early as in Induan time, came from the eastern branch of the Tethys Ocean, called Paleo-Tethys. The next migration came in Anisian time from the mid Neo-Tethys segment of the spreading ocean and entered the Germanic Basin through the Silesian-Moravian Gate. Finally when the western Neo-Tethys seaways were opened in Ladinian time, the fauna migrated *via* the Western Gate and progressed farther northward through the SW Germany.

12. The faunal assemblages (both the body and trace fossils) display a distinct impoverishment toward the inner parts of the Germanic Basin. This phenomenon was caused by the increased water salinity and oxygen depletion within the basin center.

13. New, 3rd order depositional sequences have been established for the whole Germanic Basin. Because of the facies diachroneity, the late Scythian–Anisian depositional sequences have been defined in the Polish Basin, where the Röt and lower Muschelkalk are developed in open marine carbonate facies rich in fossils of biostratigraphical importance.

The upper part of the sequence stratigraphic framework, i.e. from the middle Muschelkalk to the Gispkeuper bases on data from the western, German Basin. The proposed sequence stratigraphical scheme differs from that by Aigner and Bachmann (1992) as it contains some additional sequences of the early Anisian interval, recognised in the fully marine deposits of the Polish Basin.

14. As becomes apparent from the comparison of the Germanic sedimentary sequences with the sequences determined in the tethyan domain (Fig. 17) the influence of tectonic controls on the 3rd order cyclicity was negligible and most of the distinguished sequences resulted from eustatic controls

15. The systems tracts which build the depositional sequences in the Peri-Tethys area go in hand with changes in faunal composition. As a rule the TST is depleted in species number but comprises much more immigrants (from the Tethys) than the HST. The HST is dominated by local species and is much richer in species number than the TST assemblages. The biota accommodation could not keep pace with rapid environmental changes (energy, depth, light and oxygen supply) typical for the transgression event. In result the population became impoverished in species number represented mostly by immigrant elements. During the highstands the stabilised environmental conditions favoured faunal diversification and dominance of the local species.

16. The results of geochemical investigations of the stable isotopes and strontium content are in agreement with the other paleoenvironmental intepretations based on paleoecological and sedimentological criteria. The stable isotopes signals enabled to recognise the evolution of water chemistry related to climatic and endogenic controls. Employment of the oxygen isotopes in paleobathymetric estimation gave the maximum depth of ca. 150 m. during the maximum transgression event in the Upper Silesian subbasin.

17. Because the northern Peri-Tethys was situated within the subtropical zone, its climate was hot and arid. Only in Ladinian time the climate became more humid and milder as proved by sedimentary and paleontological indicators. The most possible cause of these changes was vigorous volcanic activity within the Tethys spreading belt. This phenomenon is well recorded in lithological characteristics and geochemical signals both in the Tethys and Germanic Basin. The Ladinian–early Carnian volcanism and topographic rejuvenation recorded in the entire basin have been causally associated with the vigorous spreading and tectonic reconstruction within the Tethys rifting belt.

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Streszczenie

EWOLUCJA ŚRODKOWOTRIASOWA PÓŁNOCNEJ PERYTETYDY I JEJ ZWIĄZKI Z ROZWOJEM OCEANU TETYDY

Joachim Szulc

Przedstawiona praca dotyczy rekonstrukcji rozwoju basenu północnej Perytetydy, (nazywanego także basenem germańskim) jako peryferyjnego basenu Oceanu Tetydy w okresie od późnego scytyku do wczesnego karniku, tzn. obejmuje ona osady retu, wapienia muszlowego i dolnego kajpru.

W celu odtworzenia ewolucji basenu dokonano konstrukcji map rozmieszczenia litofacji dla wybranych przedziałów czasowych. Przeprowadzono także korelację przestrzenno-czasową tych facji, opartą o analizę sekwencji depozycyjnych trzeciego rzędu. Badania powyższe zostały uzupełnione analizą wybranych aspektów paleoekologicznych zespołów faunistycznych występujących w basenie, jak też analizą zmian chemizmu wód zbiornika, zapisanych w sygnale izotopowym węgla i tlenu.

W czasie środkowego triasu basen germański był peryferyjną częścią Oceanu Tetydy zamkniętą od północy i wschodu poprzez Ląd Sarmacko-Skandynawski a od południa poprzez speneplenizowane masywy hercyńskie nazywane Lądem (Allemańsko)-Windelicko-Bohemskim (Czeskim). Zachodnie obrzeże basenu tworzył blok złożony z masywu Centralnego, Brabanckiego i Londyńskiego (Fig.1)

Cyrkulacja wód pomiędzy Tetydą a basenem germańskim odbywała się poprzez system obniżeń – bram i cieśnin, wykazujących często założenia tektoniczne. I tak Brama Wschodniokarpacka (BWK) była usytuowana na linii strukturalnej Teisseyre'a-Tornquista, Brama Morawsko-Śląska (BMS) zaś była kontrolowana przez uskok Morawsko-Śląski (Fig. 2).

Dane paleontologiczne wskazują, że połączenie wschodnie, tj. poprzez BWK istniało już w środkowej części wczesnego triasu (Ind), BMS zaś została otwarta z początkiem anizyku. Połączenie zachodnie powstało dopiero w ladynie. Jak jednak wynika z analizy rozmieszczenia facji w basenach Alp Zachodnich oraz ich przedpola, połączenie nie mogło odbywać sie poprzez dotąd powszechnie akceptowaną, tzw. Bramę Burgundzką, gdyż region ten w czasie środkowego triasu był obszarem lądowym, bądź co najwyżej sebhą. Nie ma też żadnych przesłanek wskazujących by obszar burgundzki był połączony z basenem SW Niemiec. Bardziej prawdopodobnym wydaje się, że połączenie zachodniej części basenu germańskiego w ladynie odbywało się obniżeniem położonym na NE od obszaru burgundzkiego. Jednym z takich przesmyków mogła być depresja Alp Reńskich (Alpenrhein Depression) mająca charakter tektonicznego obniżenia w obrębie masywu windelickiego. Dla tego połączenia wprowadzono roboczą nazwę – "Brama Zachodnia".

Rozpatrując basen germański w kontekście paleooceanograficznym, obszar ten był przez większą część środkowego triasu, bardzo rozległą strefą lagunową ("back ramp area"), o znacznym zróżnicowaniu paleobatymetrycznym, wykazującą cechy ograniczonej cyrkulacji, typowej dla basenów półzamkniętych ("semi-closed basin") (Fig. 30). Znajduje to swoje odbicie w zróżnicowaniu litofacjalnym osadów wypełniających basen, polegającym generalnie na wzroście udziału osadów ewaporatowych w kierunku zachodnim (por. Fig. 12), jak i na towarzyszące temu trendowi stopniowe ubożenie zespołu faunistycznego. Również rozkład izotopów stabilnych ^{13}C i ^{18}O (Figs. 25–29) potwierdza taki charakter basenu. Podkreślić jednak należy, że depozycja części ewaporatów, a szczególnie miąższych kompleksów ewaporatowych zawierających sól kamienną, odbywała się w najgłębszych strefach zbiornika a nie jak to dotąd przyjmowano wyłącznie w środowiskach ekstremalnie płytkiej sebhy bądź playi (Figs. 8, 12, 15).

Normalnomorskie warunki istniały w anizyku w obszarze górnośląskim, który właściwie stanowił wtedy integralną część Oceanu Tetydy. Bardzo dobrą egzemplifikacją takiej pozycji basenu śląskiego jest występowanie tu raf gąbkowo-koralowcowych (Figs. 13, 20) oddzielających strefę otwartego oceanu (Tetydy) od strefy zarafowej (t.j. basenu germańskiego *s.s.*). Jak można wnioskować z rozkładu miąższości osadów w basenie germańskim (Fig. 14) oraz z rozkładu facji (Fig. 12), obszar Śląska stanowił dość stabilny próg o głębokościach mniejszych niż głębokość depocentrów basenu germańskiego (Fig. 30), jednakże bezpośredni wpływ oceanu decydował tu o przewadze normalnomorskiej, węglanowej sedymentacji przez większą część omawianego interwału triasu.

Przedstawiony schemat stratygrafii sekwencyjnej (Figs. 8, 16) skonstruowany w oparciu o zintegrowane repery biostratygraficzne również dobrze odzwierciedla zmienność facjalną wynikającą z półzamkniętego charakteru basenu germańskiego. Ujednolicenie warunków sedymentacyjnych nastąpiło we wczesnym ladynie (fassan), kiedy po otwarciu Bramy Zachodniej basen zmienił charakter na otwarty, cechujący się lepszą cyrkulacją i wymianą wód.

Tektonicznie generowane podniesienie polskiej części basenu germańskiego, rozpoczęte już u schyłku fassanu doprowadziło do zamknięcia bram wschodnich i ograniczenia dróg komunikacji wyłącznie do systemu połączenia zachodniego.

Stwierdzony diachronizm w przebiegu otwierania i zamykania połączeń basenu germańskiego z Tetydą był pochodną spreadingu Oceanu Tetydy, postępującego ze wschodu na zachód. We wczesnym triasie centrum spreadingu usytuowane było we wschodnich odgałęzieniach zachodniej Tetydy (nazywanych niekiedy Paleo-Tetydą), w anizyku i ladynie zaś nowe, zachodnie odgałęzienia (Neo-Tetyda) ulegały otwarciu, kosztem zamykania ryftów paleotetydzkich. Naprężenia i ruchy tektoniczne rodzące się w strefie spreadingu przenoszone były na jego peryferia poprzez reaktywowane, starsze (głównie hercyńskie) uskoki, jak np. uskok Morawsko-Śląski czy też lineament Teisseyre'a-Tornquista.

Północne obszary basenu (Morze Północne, płn. Niemcy, Holandia, Anglia) były kontrolowane przez inicjalny ryfting Północnego Atlantyku. Natomiast centralna część basenu leżąca poza zasięgiem obydwu zon ryftowych, kształtowana była przez subsydencję termalną, prowadzącą do powstania bardzo miąższych wypełnień osadowych (por. Fig. 14).

Pomimo stwierdzonej silnej syndepozycyjnej mobilności tektonicznej w basenie germańskim, jego schemat stratygrafii sekwencyjnej wykazuje dużą zbieżność z sekwencjami basenów alpejskich (Fig. 17). Wydaje się to wskazywać na dominujący wpływ eustatyki na wahania poziomu morza także na peryferiach Tetydy.

Również zmiany procesów sedymentacyjnych wynikające ze zmian klimatycznych wykazują pełną paralelizację pomiędzy Tetydą i jej basenem peryferyjnym. Ożywiona aktywność tektoniczna wraz z intensywnym wulkanizmem doprowadziły u schyłku ladynu do zwilgotnienia klimatu i ożywienia sedymentacji klastycznej tak w basenach pełnomorskich (Wengen Formation, Reifling Formation, Partnach Formation), jak i w basenie germańskim (najwyższy wapien muszlowy, dolny kajper).